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DESIGN OF ELECTRICAL MACHINERY

VOLUME III

ALTERNATORS, SYNCHRONOUS MOTORS, ROTARY CONVERTERS

75 K.V.A. Engine-driven Alternating-current Generator (Westinghouse Co.)

Frontispiece

DESIGN
OF
ELECTRICAL MACHINERY

A TREATISE FOR THE USE, PRIMARILY, OF STUDENTS IN ELECTRICAL ENGINEERING COURSES

VOL. III

ALTERNATORS, SYNCHRONOUS MOTORS, ROTARY CONVERTERS

BY

WILLIAM T. RYAN, E.E.
Assistant Professor of Electrical Engineering, The University of Minnesota

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DESIGN OF ELECTRICAL MACHINERY

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PREFACE

THE purpose of this volume is to treat alternating-current generators, synchronous motors, and rotary converters. It contains what the author believes will be of most service to the student who is just entering upon his experience as a designer.

A more comprehensive study of the principles and phenomena underlying the calculations should be made by means of lectures, recitations, through the medium of references, etc.

Good electrical apparatus cannot be designed by any set of rules, and it must be recognized that it is not, in general, feasible to develop a finished commercial designer in a college course. However, there are certain fundamental scientific principles which can be laid down definitely and taught with precision. The student should bear in mind that while there is much in this volume that is of practical value, the main object is to present as clearly and briefly as possible the fundamental principles on which the designer necessarily rests. He should also bear in mind that he cannot expect to get any more than a training that will be of value and assistance to him, if at any time in his later experience he should decide to become a designer.

An electrical designer must also be a mechanical designer. This point is very often overlooked by the beginner. It is possible to devise some very wonderful designs from an electrical standpoint, but which when the mechanical features are considered are absolutely impractical.

Direct-current dynamos and alternating-current transformers were considered in the preceding volumes. Alternating-current generators and synchronous motors are, of course, practically one and the same problem from the standpoint of design. Only these points wherein a rotary is essentially different from either the synchronous motor or a direct-current generator are considered.

Special attention has been given to the arrangement of the work with regard to the order of the process of carrying out the calculations.

The author has drawn very largely upon information obtained from the manufacturing companies. He desires to acknowledge his indebtedness to the above companies, and to express his appreciation of their courtesy for permission for use of illustrative cuts, drawings, etc. Also to many others whose valuable suggestions have been utilized in preparing this work.

WILLIAM T. RYAN.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
September, 1912.

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DESIGN OF ELECTRICAL MACHINERY

VOLUME III.—ALTERNATORS, SYNCHRONOUS MOTORS, ROTARY CONVERTERS

CHAPTER I

TYPES OF ALTERNATING CURRENT GENERATORS AND THEIR CHARACTERISTICS

A NUMBER of types of alternating current generators have been designed and constructed, but, as in many other lines of apparatus, there has been a gradual elimination and standardization, until at present nearly every alternating current generator is of the revolving field type. Alternating current generators, like direct current dynamos, have field poles and an armature; but the commutator is replaced by slip rings, which either receive direct current for exciting the rotating field or deliver alternating current to brushes rubbing on them when the armature rotates. The absence of a commutator eliminates many of the problems met with in the design of a direct current machine; however, the questions of regulation, wave form, armature inductance, etc., present problems which are equally as formidable.

Alternating current generators are usually classified as follows:

(1) Revolving field type.
(2) Revolving armature type.
(3) Inductor type.

A classification might also be made upon the current generated, as, single-phase, two-phase, three-phase, six-phase, etc. Any one of the three types may, of course, be either single-phase or polyphase. The number of phases does not affect the design as much as might at first be supposed, except in the calculation of the space required for armature conductors, heating effects, regulation, and armature reaction, as will be seen later.

Still another classification and a much better one for the purpose of design is as follows:

(1) Bracket type.
(2) Two-bearing pedestal type.
(3) Three-bearing pedestal type.
(4) Water-wheel type.
(5) Engine type.
(6) Turbine type.

Figs. 1 to 12 illustrate these different types. In case of engine-type generators, the manufacturer is usually required to furnish only the stator and rotor, the extra bearing pedestal, etc., being supplied by the manufacturer of the engine. Alternating-current generators are usually rated in kilo-volt amperes, (K.V.A.), instead of in kilowatts. Very often the same machine has two ratings. For example, the armature and field of a certain 100 K.V.A. machine is guaranteed not to increase in temperature more than 30° C. This same machine is rated at 120 K.V.A. and the ultimate temperature rise of the armature and field coils is given as 40° C. If the load is 125 K.V.A. the two-hour limit is given as 45° C. The 25 per cent overload ultimate temperature rise on the 40° C. machine is specified as 55° C. The momentary overload which a machine will take care of is specified at from 150 per cent to 200 per cent of normal load. The guaranteed regulation of the 30° C. machine referred to above was 6 per cent on normal load (100 K.V.A.) unity power factor and of the 40° C. machine, 8 per cent (120 K.V.A.). Small machines have poorer inherent regulation than large machines. Eight to 10 per cent is very good for a 25 K.V.A. machine running at say 1200 r.p.m. Five to 6 per cent

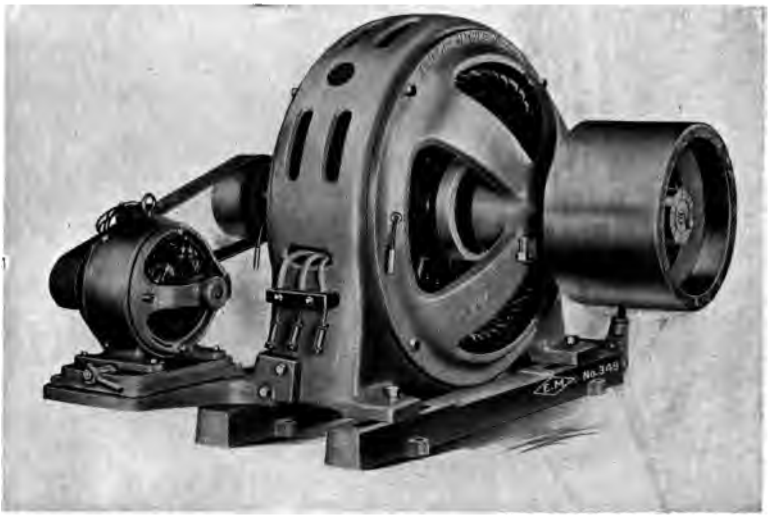


FIG. 1.—Bracket Type Alternating-current Generator (Electric Machinery Co.).

regulation would be expected for a 200 K.V.A. alternator running at say 600 r.p.m. Large slow-speed machines should give still better results. Sometimes machines are purposely designed with a rather poor inherent regulation and then used in connection with the Tirrill or some other voltage regulator. Ordinarily an alternator is designed for an ultimate temperature rise of 40° C. The A.I.E.E. standardization rules are:

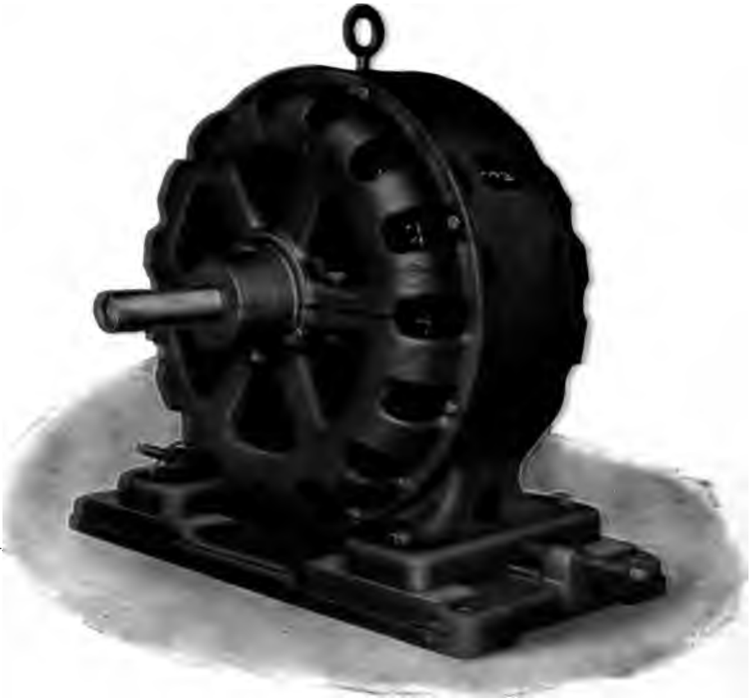


FIG. 2.—Bracket-type Alternator (Westinghouse Co.).

"*General.* The temperature of electrical machinery under regular service conditions should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

"In commutating machines, rectifying machines, pulsating-current generators, synchronous machines, synchronous commutating machines, and unipolar machines, the temperature rise in the parts specified should not exceed the following:

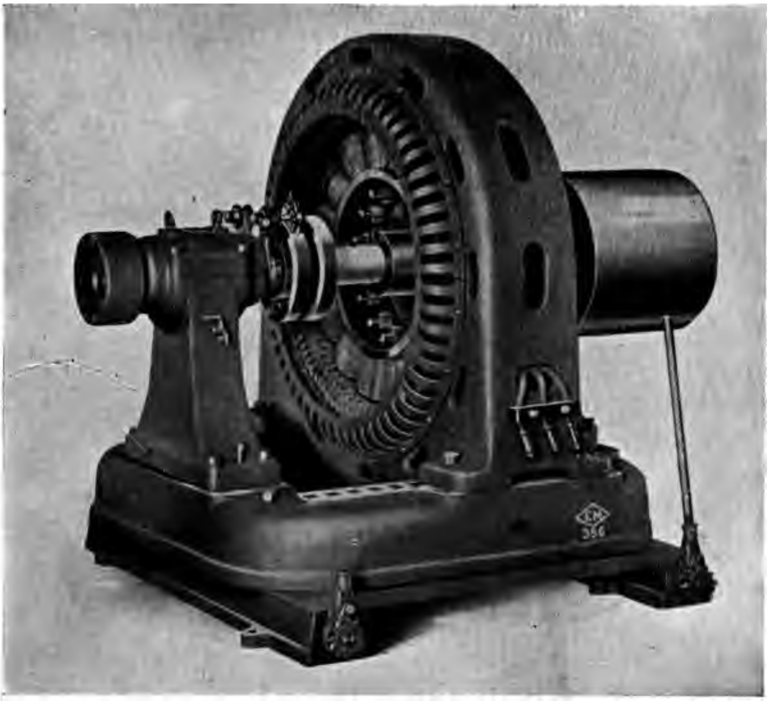


Fig. 3.—Two-bearing Pedestal-type Alternator (Electric Machinery Co.).

"Field and armature, 50° C.

"Collector rings, 65° C.

"Bearings and other parts of the machine, by thermometer, 40° C.

"*Large Apparatus.* Large generators, motors, transformers or other apparatus in which reliability and reserve overload capacity are important, are frequently specified not to rise in temperature more than 40° C. under rated load, and 55° C. at 25 per cent rated overload.

"*Normal Conditions.* Overload guarantees should refer to normal conditions of operation regarding speed, frequency, voltage, etc., and to non-inductive conditions in alternating-current apparatus, except where a phase displacement is inherent in the apparatus.

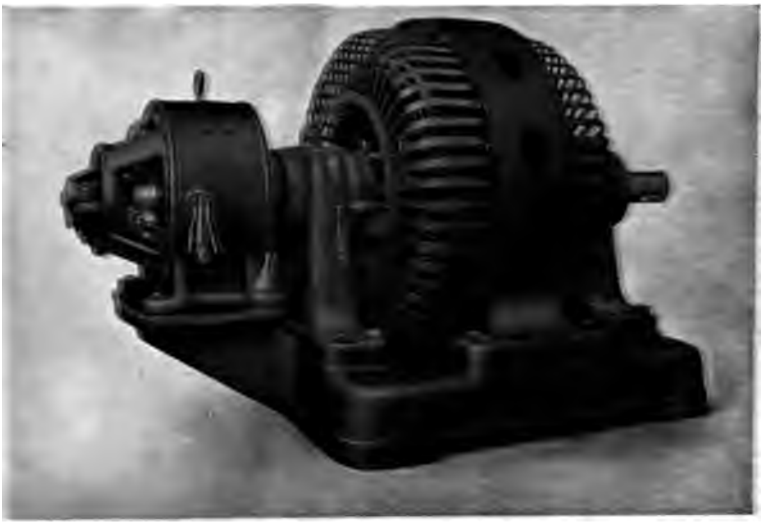


FIG. 4.—Two-bearing Pedestal Generator with Direct-connected Exciter, 200 K.V.A., 600 R.P.M. (Westinghouse).

"*Overload Capacities Recommended.* The following overload capacities are recommended:

"*a. Generators.* Direct-current generators and alternating-current generators 25 per cent for 2 hours.

"*b. Motors.* Direct-current motors, induction motors, and synchronous motors, not including railway and other motors intended for intermittent service, 25 per cent for 2 hours, and 50 per cent for 1 minute. (The additional temperature rise at 25 per cent overload not to exceed 15° C. above those specified for rated loads.) The values 40° C. for the armature and field coils and 55° C. at 25 per cent overload are recommended for most purposes."

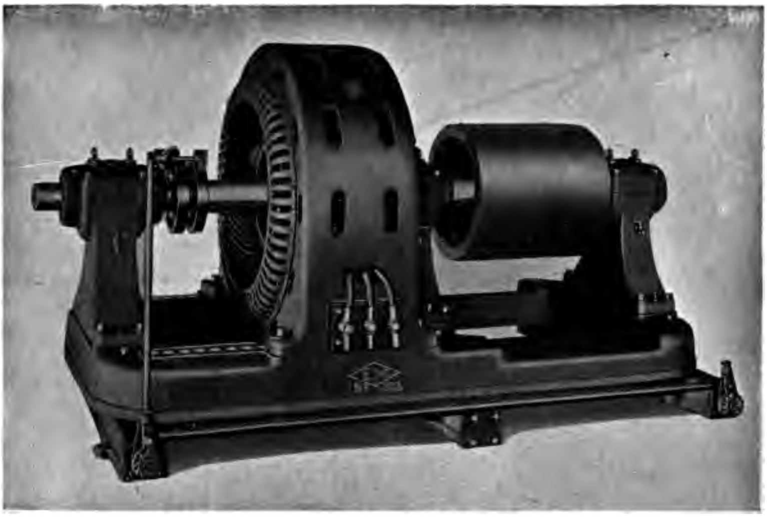


FIG. 5.—Three-bearing Pedestal Type (Electric Machinery Co.).

Effective E.M.F. Generated. It will be assumed that the flux density around the armature varies from point to point in accordance with the sine law. If the conductors of a coil side are concentrated in a single narrow slot the effective E.M.F. is given by the equation

$$E_a = \frac{2.22 \phi f Z}{10^8 a}, \tag{1}$$

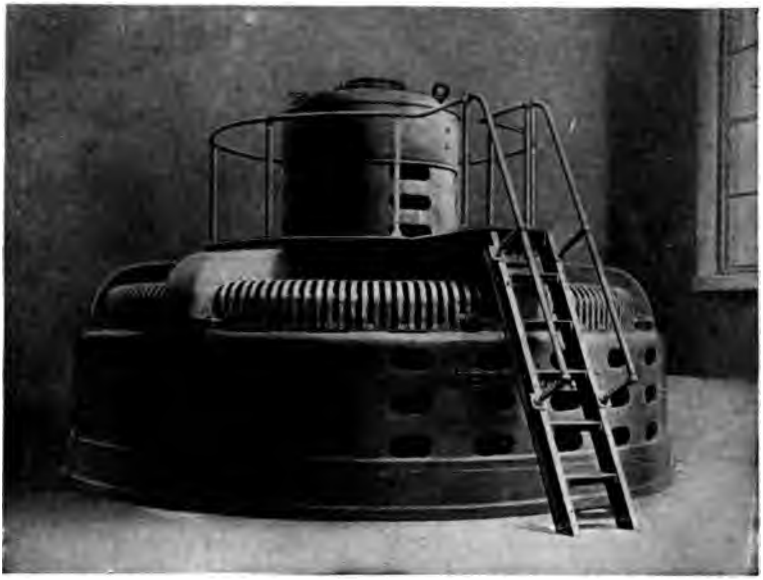


FIG. 6.—An 1875-K.V.A., 6600-volt, Three-phase, Water-wheel Generator (Westinghouse).

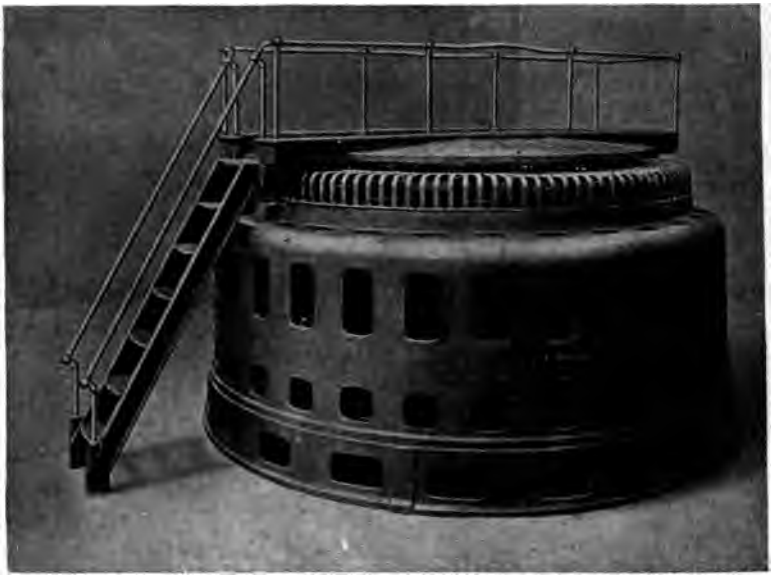


FIG. 7.—A 5000-K.V.A., 6000-volt, 3-phase, Water-wheel Generator (Westinghouse).

where ϕ = maxwells of flux per pole;

f = frequency in cycles per second;

Z = number of inductors in series, usually is the number per phase;

a = number of armature circuits per phase.

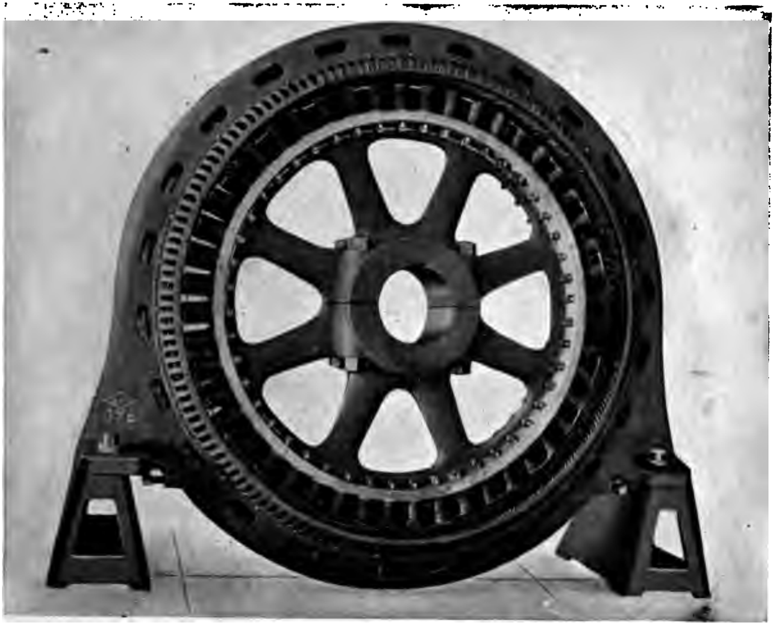


FIG. 8.—Slow-speed Engine-type Alternator (Electric Machinery Co.).

If the coil side is distributed between two or more slots the E.M.F. will be reduced. The E.M.F. for the wires in as many slots as there are poles may be calculated by formula (1), and can then be compounded by the parallelogram method, taking into consideration the phase difference due to the displacement of the slots.

Suppose, for example, that the coil side is placed in two slots, and that the distance between the two slots is equal to one-third of the pole pitch. (See Fig. 13.)

The whole winding may be considered as made up of two parts and the E.M.F. in each part would be given by Eq. (1). When we compound two equal electromotive forces having a phase difference $\frac{\pi}{3}$ or 60° we get a resultant which is equal to $\sqrt{3}$ or 1.73 times either component.

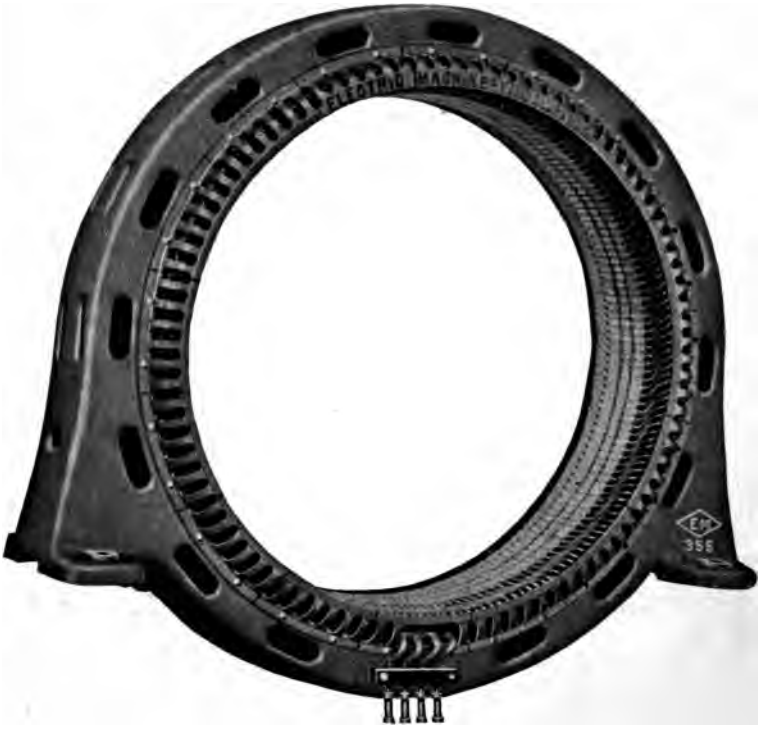


FIG. 9.—Stator of 200-K.V.A., 225-R.P.M. Engine-type Alternator (Electric Machinery Co.).

Therefore for two slots per pole per phase, where the distance between the slots is 60° the value 2.22 becomes

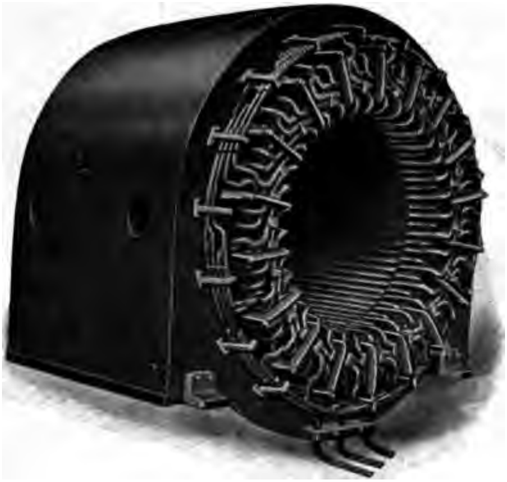


Fig. 10.—Stator Turbine-type Alternator (Westinghouse).

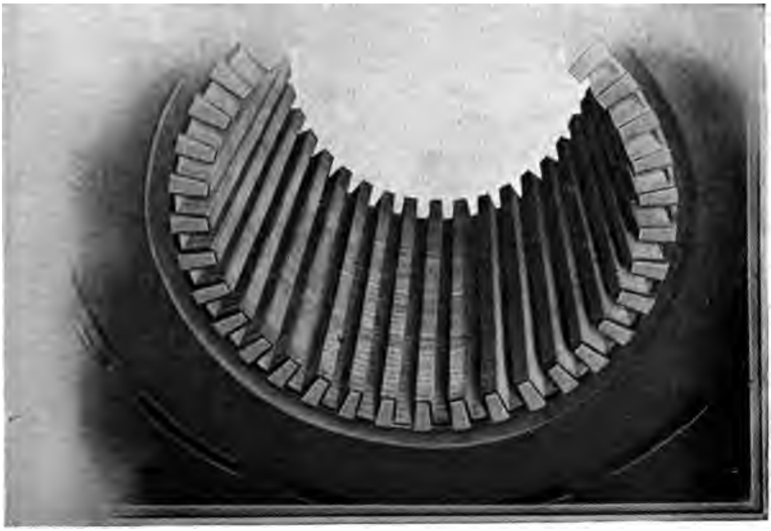


Fig. 11.—Stator Turbine-type Alternator (Westinghouse).

$2.22\sqrt{3}$ divided by 2 or 1.92, and the equation for the effective E.M.F. would be

$$(2)\qquad E_a = \frac{1.92\phi f Z}{10^8 a},$$

where, ϕ, f, Z and a have the same significance as in Eq. (1).

We will next consider the case of a distributed winding, that is, where there are so many equally spaced slots that the winding is practically equivalent to one in which the wires lie side by side upon the surface of the armature. Let each coil side occupy $\frac{\alpha}{\pi}$ of the space between two adjacent poles. (See Fig. 14.)

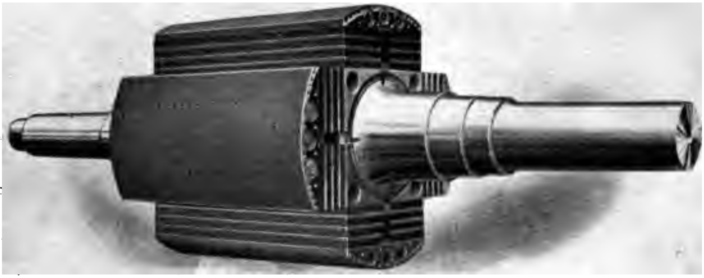


FIG. 12.—Rotor Turbine-type Alternator (Westinghouse).

If the wires were all simultaneously under the center of a pole the E.M.F. would be given by the equation

$$E_a = \frac{2.22\phi f Z}{10^8 a}.$$

Assuming that the E.M.F. of each wire varies sinusoidally, reaching its maximum value under the middle of a pole, it will be reduced from this maximum value to a value which may be represented by

$$\frac{1}{\alpha}\int_{-\frac{1}{2}\alpha}^{+\frac{1}{2}\alpha}\cos\alpha d\alpha=\frac{\sin\frac{1}{2}\alpha}{\frac{1}{2}\alpha}.$$

The effective E.M.F. will then be

$$E_a=2.22\frac{\frac{\sin\frac{1}{2}\alpha}{\frac{1}{2}\alpha}\phi fZ}{10^8a}. \tag{3}$$

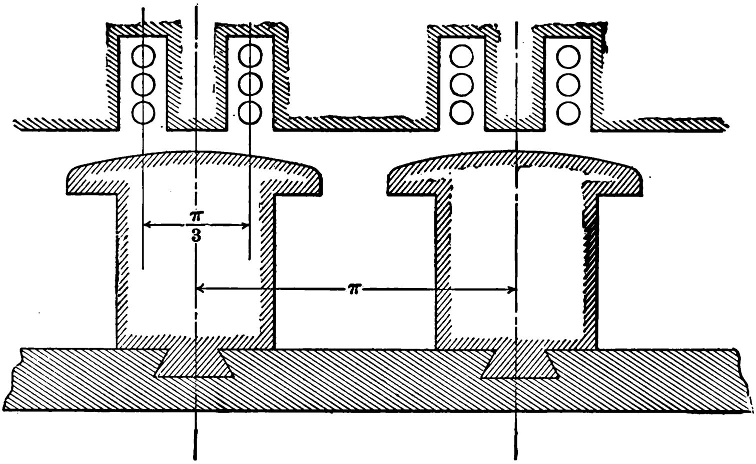


Fig. 13.

If we have one narrow slot per pole per phase then α is a very small angle, and since for very small angles the sine of the angle, is practically equal to the angle itself in π measure the quantity $\frac{\sin\frac{1}{2}\alpha}{\frac{1}{2}\alpha}$ would be equal to unity, and we obtain from Eq. (3), Eq. (1).

For a three-phase distributed winding where each coil-side has a width equal to one-third the pole pitch

$$\alpha = \frac{\pi}{3} = 60^\circ,$$

$$\sin \tfrac{1}{2}\alpha = \sin 30^\circ = 0.5,$$

$$\frac{\sin \frac{1}{2}\alpha}{\frac{1}{2}\alpha} = \frac{0.5}{\frac{\pi}{6}} = .955.$$

$$(4) \qquad E_a = \frac{(2.22)(.955)(\phi)(f)(Z)}{10^8 a} = \frac{2.12\phi f Z}{10^8 a}.$$

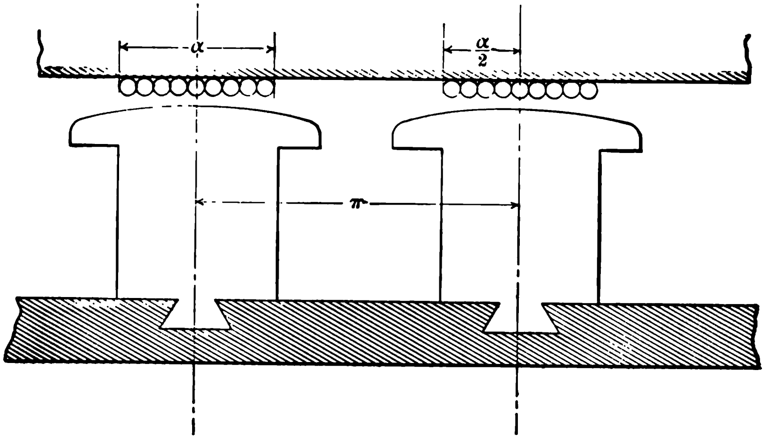


FIG. 14.

If we had a single-phase winding uniformly distributed over the armature surface then,

$$\frac{\sin \frac{1}{2}\alpha}{\frac{1}{2}\alpha} = \frac{\sin 90^\circ}{\frac{\pi}{2}} = \frac{2}{\pi} = .636.$$

$$(5) \qquad E_a = \frac{(2.22)(.636)(\phi)(f)(Z)}{10^8 a} = \frac{1.41\phi f Z}{10^8 a}.$$

A general statement of the equation for the effective E.M.F. would be as follows:

$$E_a = \frac{K \phi f Z}{10^8 a}, \tag{6}$$

where,

$$K = \frac{2.22 \sin \frac{1}{2}\alpha}{\frac{1}{2}\alpha}.$$

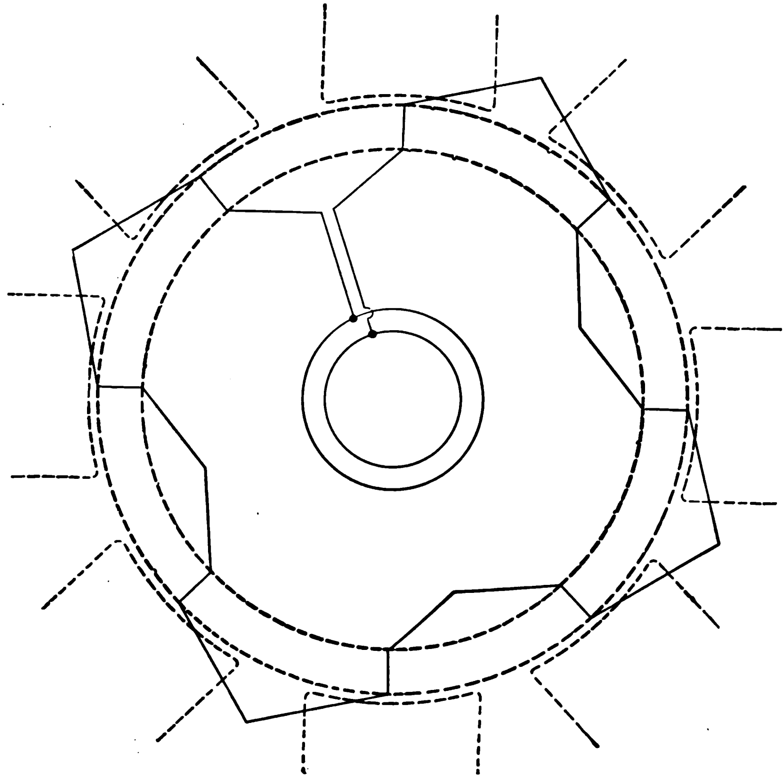


Fig. 15.—Single-phase Open-winding, One Slot per Pole.

The value of K will vary from 1.41 for a uniformly distributed single-phase winding, to 2.22 for a concentrated winding. K should be determined for the particular case under consideration and then substituted in the general equation for effective E.M.F.

The various types of alternator armature windings may be divided into open-type windings and closed-type windings. Fig. 15 shows a single-phase open winding with one slot per pole.

The most familiar type of closed winding is found in the rotary converter. This is simply an ordinary D.C. generator with taps taken from certain points on the armature winding. If single phase and bipolar, we would tap two diametrically opposite points on the armature winding, as indicated in Fig. 16.

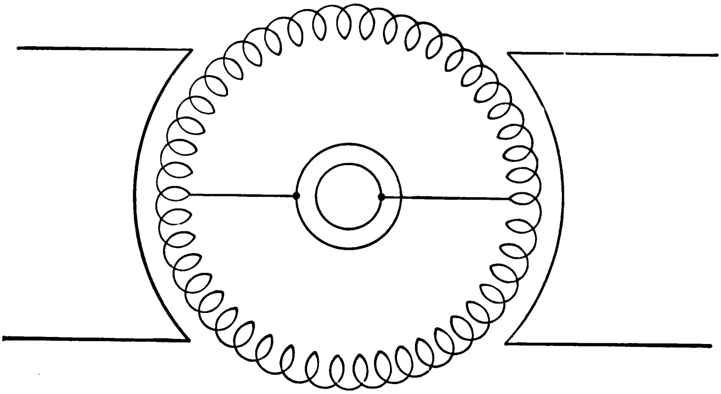


FIG. 16.

If the machine is multipolar and is lap wound, the connections to the slip rings would be joined to all the equipotential points on the winding, so that each slip ring would have as many connections as there are pairs of poles, or $\frac{a}{2}$.

The effective alternating E.M.F. is equal to .707 times the direct E.M.F.

The connections to the slip rings for a three-phase bipolar rotary converter are shown in Fig. 17. The alternating E.M.F. is 0.61 times the direct E.M.F.

For a four-phase machine, the alternating E.M.F. would be 0.50 times the direct E.M.F. and for a six-phase machine, the ratio would be 0.353.

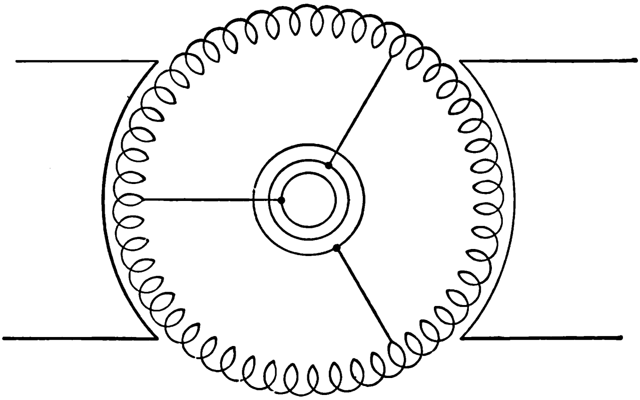


FIG. 17.

A four-pole three-phase rotary would have two connections to each slip ring if it were provided with a lap winding, three if it had six poles, etc., and there would be as many armature circuits per phase as there are pairs of poles.

Fig. 18 illustrates a two-phase open-type winding for an 8-pole machine with one slot per pole per phase.

Fig. 19 illustrates a three-phase open-type winding for an 8-pole machine with one slot per pole per phase. The three electromotive forces are 120 electrical degrees apart. It should be considered as three separate single-phase windings and then the three windings may be connected in either star or delta. If they are connected in star, the E.M.F. between the slip rings will be $\sqrt{3}=1.73$ times the E.M.F. induced in one of the three separate single-phase

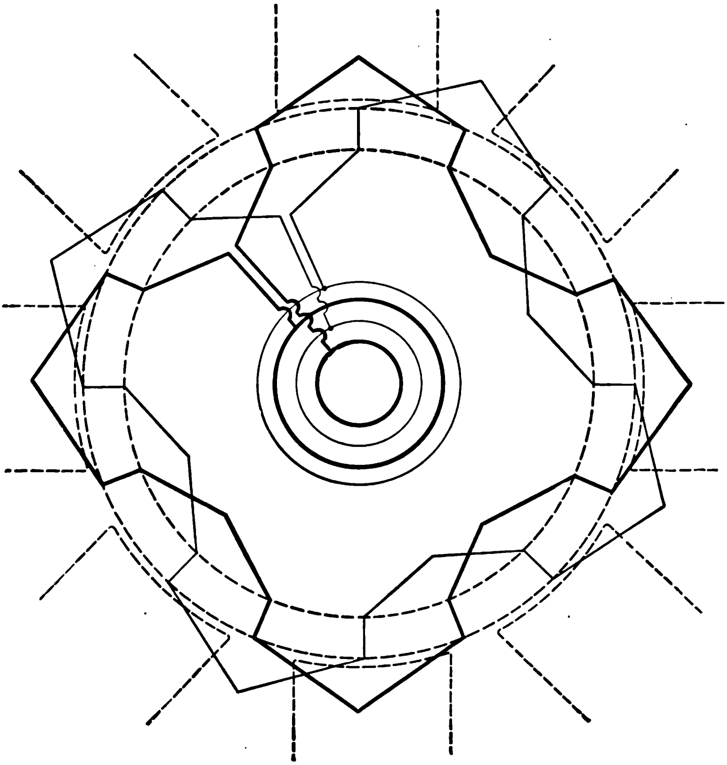


FIG. 18.—Two-phase Open-type Winding.

windings. If connected in delta, the E.M.F. will be equal to that which would be produced by one of the three windings, but the current in each of the three leads coming from the armature will be $\sqrt{3}=1.73$ times the current in each one of the three windings.

The ratio of pole face to pole pitch varies with different designers. The larger the percentage of pole face to pole pitch the greater the magnetic leakage. It is usually considered good practice to keep the percentage of the armature covered by the poles down to between 60 and 65 per cent.

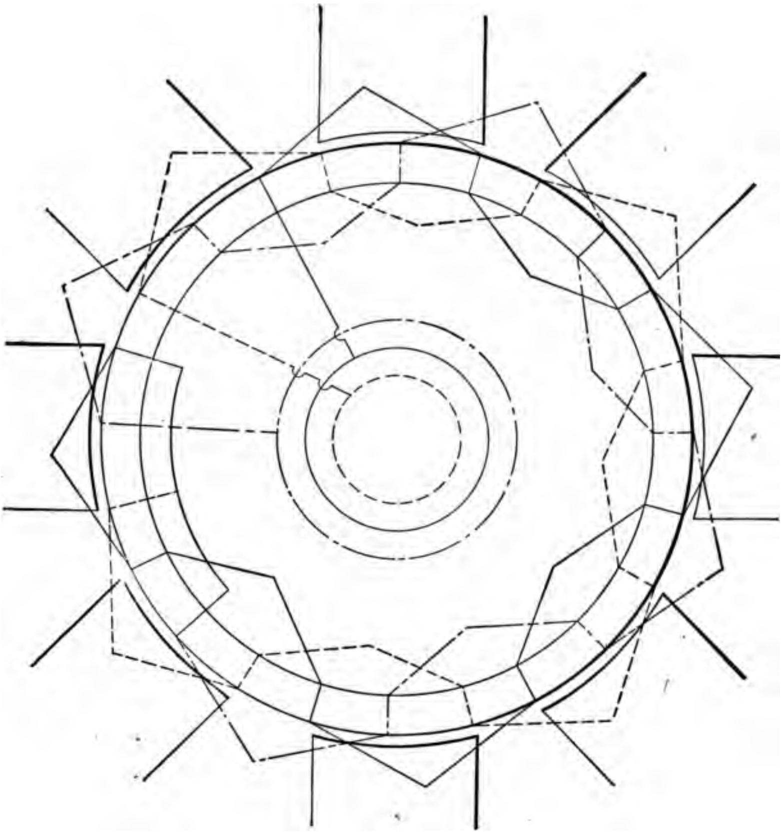


Fig. 19.—Three-phase Open-type Winding.

The number of slots per pole for two- and three-phase machines must be divisible by the number of phases, and when the same stampings are to be used for both two- and three-phase machines must be divisible by six.

According to Rushmore (Trans. A.I.E.E., Vol. XXI) most engine-type alternators are built with six or twelve slots per pole, twelve slots per pole being used where the kilowatts output per pole are high, and it is not desirable to increase the length of the armature to the amount necessary for six slots. Nearly all engine-driven alternators have six slots per pole. Many three-phase alternators, however, are designed with nine slots per pole or three per pole per phase.

E.M.F. Diagrams. If the coefficient of self induction of an alternator armature were constant at all loads, no matter what the power factor or excitation were, the vector diagram would be as follows:

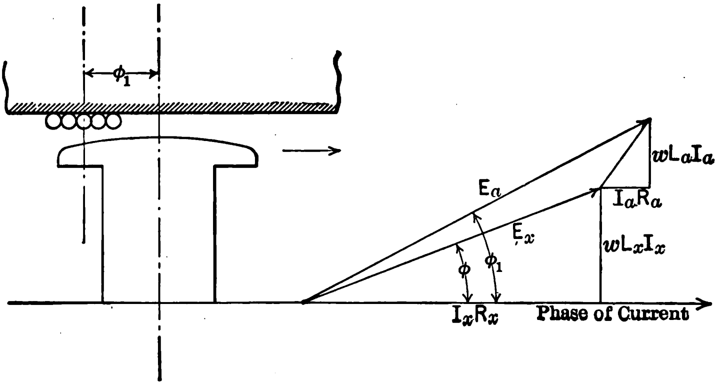


FIG. 24.

The E.M.F. E_a which is induced in the armature is the hypothenuse of a right-angled triangle one side of which is equal to the sum of the internal and external ohmic drops, and the other to the total inductive pressure drop, both internal and external.

The angle ϕ_1 is the angle by which the current lags behind the induced E.M.F. Where the angle $\phi_1 = 0$, the current would be a maximum when the center of the pole coincided with the center of a coil side. The angle ϕ_1 means then that the center of the pole has gotten by the center of a coil-side by this angle, before the current reached its maximum value.

When an alternator is working under load, the factors affecting the voltage drop are (1) armature resistance, (2) armature reactance, and (3) demagnetization or magnetization of the armature ampere turns, depending on the power factor.

We will now construct the E.M.F. diagram as follows:

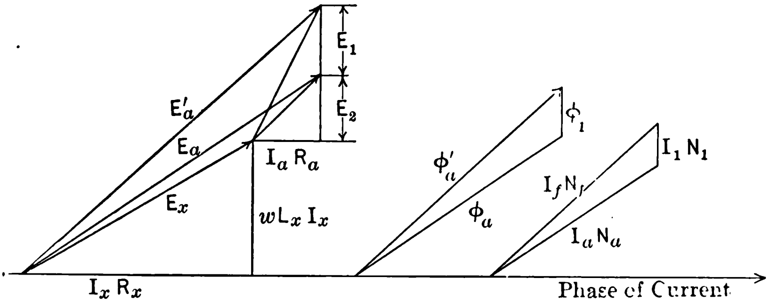


FIG. 25.

E_a' = E.M.F. which would be induced were there no armature resistance, reactance, or magnetization;

E_a = actual E.M.F. induced;

E_1 represents the effect of the armature ampere turns on the flux;

E_2 represents the leakage or armature reactance drop.

The electromotive forces E_a' and E_1 are, of course imaginary, as is also the flux ϕ_a' and ϕ_1. The ampere turns

I_fN_f and I_1N_1, however, are real quantities, and act on a common magnetic circuit in such a way that their resultant produces the actual flux ϕ_a.

According to Thomälen, for single-phase machine the armature reaction in ampere turns per pair of poles is:

$$I_1N_1 = \frac{0.9I_aZ}{2p}, \tag{7}$$

where I_1N_1 = number of ampere turns per pair of poles;
Z = number of wires in series on the armature;
p = number poles;
I_a = effective value of the armature current.

In the above formula it has been assumed that the coil-side is under a pole all the time. If the percentage of the armature surface covered by the pole shoes is 66⅔ per cent, then according to Kapp,

$$I_1N_1 = \frac{.736I_aZ}{2p}, \tag{8}$$

and if 50 per cent of the armature surface is covered by the poles, then,

$$I_1N_1 = \frac{0.8I_aZ}{2p}. \tag{9}$$

For values in between 50 and 66⅔ per cent it is sufficiently accurate to interpolate.

For a three-phase machine in which the polar arc is two-thirds of the pole pitch the armature reaction is given as:

$$I_1N_1 = \frac{2.12I_aZ}{2p}, \tag{10}$$

where Z = number of wires in series per phase, and I_a, I_1, N_1, and p have the same significance as before.

I_1N_1 = armature reaction in ampere turns per phase per pair of poles.

The effect of armature reaction is to cross magnetize as long as E_a and I_a are in phase. If the current lags 90 degrees behind the E.M.F. then the armature reaction would be directly opposed to the field magnets. If the current leads the E.M.F. then this demagnetizing effect becomes negative, and the E.M.F. may rise instead of falling off with the load.

Synchronizing Power. If two or more alternators are working in parallel, they must of course run in synchronism. The mechanical engineer is often puzzled when he observes the fact that the connecting rods of two engines driving alternators in parallel will remain in step perfectly hour after hour. The mutual influence which the generators exert on one another, tending to maintain synchronism, is known as their synchronizing power.

It is assumed in the following that the bus-bar E.M.F., E_x, is not affected by the machine we have under consideration.

In Fig. 26 E_a is the induced E.M.F. in the machine under consideration. E_x is the bus-bar voltage, I_aR_a and ωL_aI_a are the ohmic and inductive drops respectively in the armature under certain conditions of load.

Fig. 27 is the same except that it is drawn for a larger load, therefore for more current. The values E_a and E_x are the same in both figures. In Fig. 27 O' is used as a center and an arc struck with E_a. $O'B'$ is made equal to I'_aR_a and $B'O$ equal to $\omega L_aI'_a$.

Then with O as a center and E_x as a radius an arc is struck intersecting the arc struck from O' with E_a at C. Then CB is made equal to $O'B'$ and BD equal to $B'O$ and E_a drawn from D to O, thus completing the diagram.

Fig. 26 and Fig. 27 differ in one very important point, namely—the angle α between E_a and E_x has increased. A study of Figs. 26 and 27 indicate to us at once that as the load is increased, there is an increase in the angle between E_a and E_x, or vice versa. Therefore if the engine driving the alternator tends to increase in speed, it is automatically given a heavier load, and if it tends to decrease in speed, it is given a smaller load, hence is kept in synchronism with the other engines by this synchronizing power of the armature. It is further seen that the machine has its greatest synchronizing power when the inductive reactance of the armature is equal to its resistance; also that its synchronizing power disappears when the armature inductance is zero.

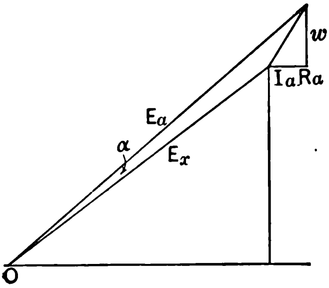


FIG. 26.

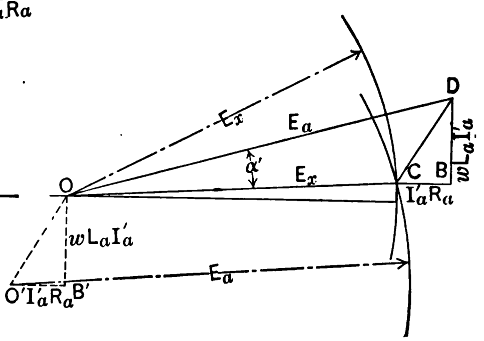


FIG. 27.

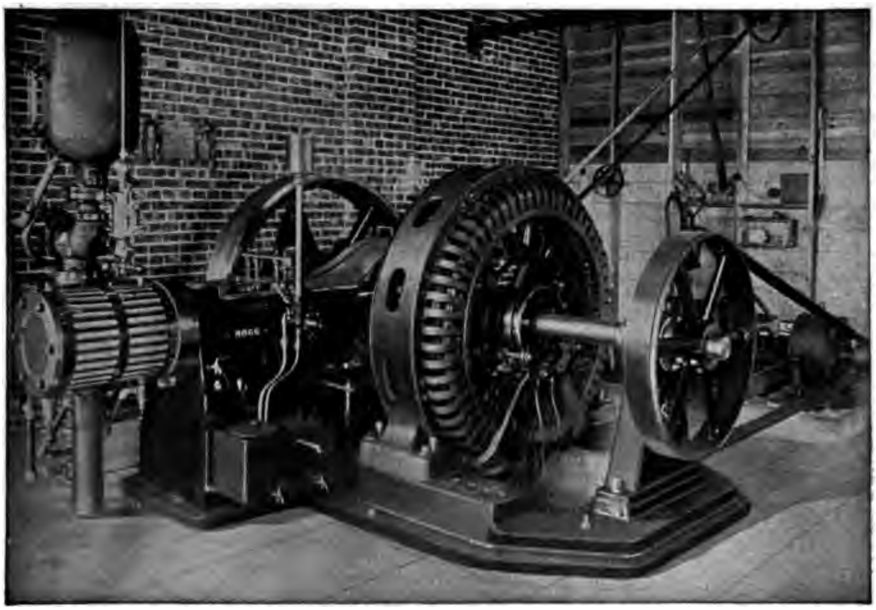


Fig. 28.—50-K.V.A., 2400-volt, Three-phase, 60-cycle Generator (Westinghouse).

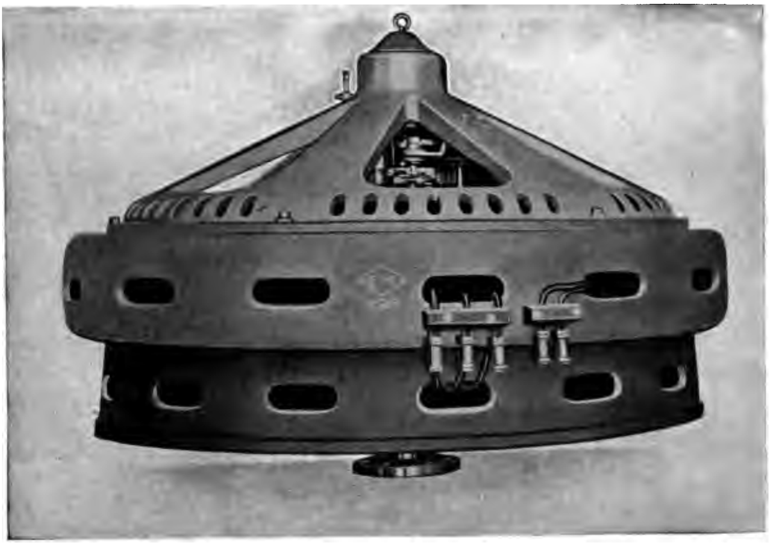
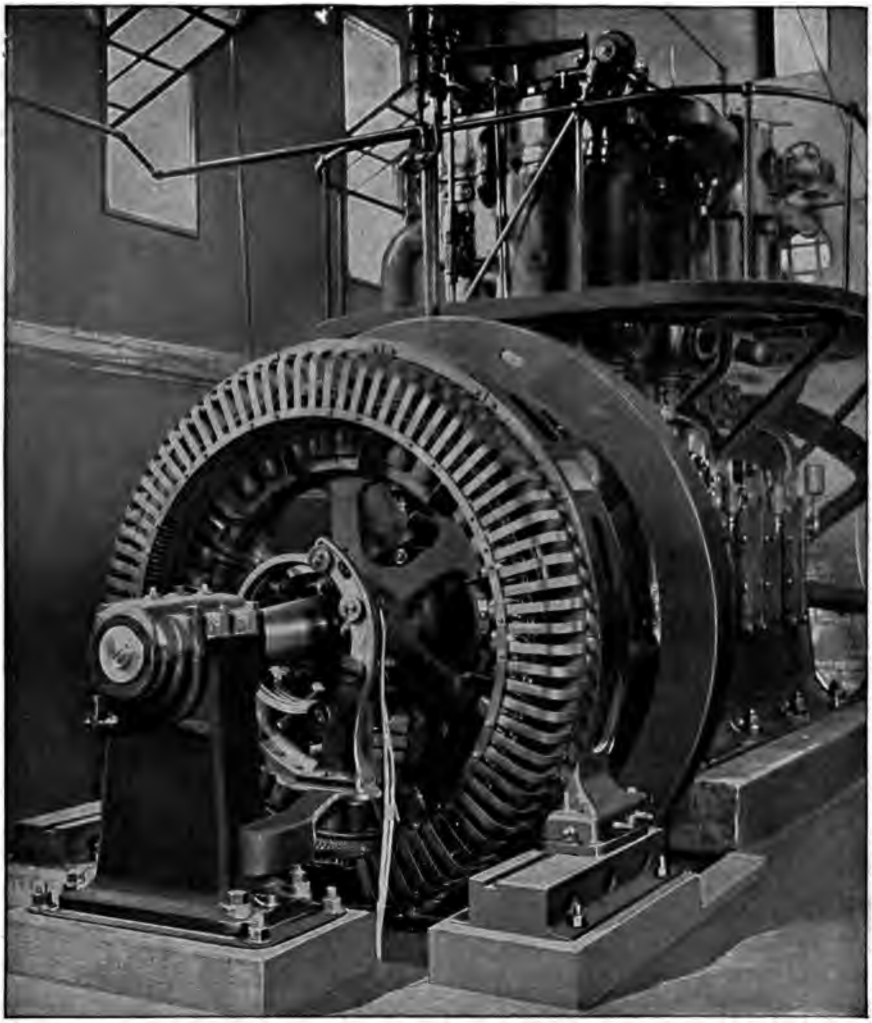


Fig. 29.—Vertical-type Water-wheel Generator (Electric Machinery Co.).



(Fig. 30.—260-K.V.A., 4000-volt, Three-phase, 60-cycle Generator Driven by Gas Engine (Westinghouse).

CHAPTER II

METHOD OF DESIGNING ALTERNATORS AND SYNCHRONOUS MOTORS

GIVEN the output, voltage, number of phases, frequency, type, efficiency, required regulation, allowable temperature rise, etc., the design is proceeded with as follows: bearing in mind, of course, that in some places it will be necessary to make estimates in order to proceed with the design, which later on are corrected. This cannot be avoided. In the following method an attempt has been made to so arrange the order of the process of making the calculations that this necessity of making estimates of later results is reduced to a minimum.

(A) Type

If the machine is a very small one, it may be of the revolving armature type, otherwise the revolving field type is usually selected. The design of a revolving armature alternator is very similar to the design of a direct-current generator. About the only difference is that slip rings are provided instead of a commutator, and the number of poles must be equal to two times the frequency divided by the number of revolutions per second. This usually means more poles than would ordinarily be provided on a direct-current generator. The prevailing peripheral velocities of alternator armatures are therefore higher than for D.C. machines.

The method of design laid down in Volume I, with the modifications pointed out above and a knowledge of voltage and phase relationships, as given in Chapter I of this volume will suffice for the design of the revolving armature type. What follows will refer primarily to the revolving field types.

(B) Speed and Frequency

The speed depends to a considerable degree upon the frequency. The frequency is usually determined from the conditions under which the machine is to be operated. If the load is to be entirely or largely a lighting load the frequency is usually made 60 cycles per second. If the load is entirely motors, or rotary converters, or if the power output is transmitted a very long distance, say 150 miles at a potential of, say, 150,000 volts, it is usually generated at a frequency of 25 cycles per second. Table I gives the relationship between output and speed for 60-cycle generators of different types. Table II covers 25-cycle machines.

(C) Number of Poles

The number of poles is fixed by the frequency and the speed, hence is also determined from Tables I and II.

TABLE I

RELATION BETWEEN OUTPUT AND SPEED FOR 60-CYCLE ALTERNATORS

Output in K.V.A.	Speed, r.p.m. Belted Type.	Speed, r.p.m. Engine Type.	Speed, r.p.m. Water Wheel.
10	1800		
50	1200	360	
100	900	300	720
200	600	240	514
300	514	200	450
400	450	180	400
500	380	150	360
600	360	138	327
800	300	120	277
1000	277	100	240
1200	....	90	214
1500	....	90	187
2000	....	82	187
3000	....	75	150

TABLE II

RELATION BETWEEN OUTPUT AND SPEED FOR 25-CYCLE ALTERNATORS

Output in K.V.A.	Speed, r.p.m. Belted Type.	Speed, r.p.m. Engine Type.	Speed, r.p.m. Water Wheel.
10	750		
50	750		
100	500	167	500
200	500	150	500
300	375	136	375
400	375	125	300
500	300	116	300
600	250	107	250
800	214	100	250
1000	187	93	214
1200	....	88	214
1500	....	82	187
2000	....	75	187
3000	....	75	167

(D) Diameter and Length of Armature

$$D^2L = \frac{(Q)(\text{K.V.A.})(10^4)}{\text{r.p.m.}}, \tag{11}$$

where D = outside diameter of armature laminations in inches;

L = length of armature iron including ventilating ducts in inches;

Q = an output coefficient.

In Tables III, IV and V are given the output coefficients for 60-cycle alternators.

TABLE III

OUTPUT COEFFICIENTS FOR HIGH-SPEED ALTERNATORS

Output in K.V.A.	Q	Output in K.V.A.	Q
10	20.0	300	4.4
25	10.0	500	4.1
50	8.0	800	3.9
75	6.8	1000	3.8
100	6.0	2000	3.65
150	5.1	3000	3.5
200	4.7	5000	3.45

TABLE IV

OUTPUT COEFFICIENTS FOR SMALL ENGINE TYPE OR LOW-SPEED BELTED ALTERNATORS

SPEED 360 TO 120 R.P.M.

Output in K.V.A.	Q	Output in K.V.A.	Q
50	6.00	350	3.4
100	4.80	400	3.3
150	4.20	450	3.2
200	4.00	500	3.12
250	3.70	550	3.06
300	3.60	600	3.0

TABLE V

OUTPUT COEFFICIENTS FOR LARGE HIGH-SPEED ALTERNATORS

SPEED 720 TO 450

Output in K.V.A.	Q	Output in K.V.A.	Q
1000	3.8	3500	3.49
1500	3.7	4000	3.46
2000	3.6	5000	3.42
2500	3.55	6000	3.32
3000	3.51	7500	3.20

TABLE VI

OUTPUT COEFFICIENTS FOR LARGE SLOW-SPEED ALTERNATORS

Output in K.V.A.	Q	Output in K.V.A.	Q
1000	2.7	3500	2.42
1500	2.6	4000	2.38
2000	2.55	5000	2.30
2500	2.50	6000	2.22
3000	2.46	7500	2.16

Having determined the product D^2L, we must next assume either D or L. We have the choice of either taking a large diameter and making the armature short, or taking a small diameter and making the armature long. In machines of small diameter, the poles are crowded together, giving poor opportunity for regulation. With large diameters, the field coils are farther apart, the peripheral speed is higher, therefore the cooling of the armature is much greater. But again, machines of larger diameter require heavier castings, and therefore present greater difficulties in handling. Tables VII and VIII are intended to be used as a guide in deciding on the diameter. Table VII was made up from an actual line of machines made by a reputable manufacturing company.

The outside diameter is to the outside of the armature laminations, and the inside diameter is the bore of the stator.

TABLE VII

Diameters, Lengths, and Output Coefficients of Alternator Armatures

Output, K.V.A.	Outside Diam., Inches.	Inside Diam., Inches.	Length Armature, Inches.	Speed, r.p.m.	Frequency Cycles per Second.	Q
30	$25\frac{5}{16}$	$18\frac{11}{64}$	4	1200	60	10.3
50	$27\frac{1}{2}$	20	$4\frac{1}{2}$	1200	60	8.2
75	34	26.4	5	900	60	7.05
100	34	26.4	6	900	60	6.25
150	39	$30\frac{5}{8}$	$7\frac{5}{16}$	900	60	6.65
150	$48\frac{1}{2}$	$40\frac{1}{4}$	$5\frac{3}{4}$	600	60	5.45
200	$48\frac{1}{2}$	$40\frac{5}{16}$	7	600	60	5.00

TABLE VIII. (ESTERLINE)

DIAMETERS OF BELTED ALTERNATOR ARMATURES

Output in K.V.A.	Outside Diameter in Inches.			Ratio of Length to Diameter of Core.	
	Min.	Mean.	Max.	Min.	Max.
30	14	17	23	.75	.33
50	16	20	29	.71	.31
75	20	28	35	.67	.28
100	22	34	40	.63	.26
150	26	42	46	.58	.23
200	36	51	58	.55	.22

TABLE IX

DIAMETERS, LENGTHS, AND OUTPUT COEFFICIENTS OF ENGINE TYPE ALTERNATORS

Output, K.V.A.	Outside Diam., Inches.	Inside Diam., Inches.	Length Armature, Inches.	Speed, r.p.m.	Frequency Cycles per Second.	Q
50	44	37.72	5	300	60	5.8
55½	44	38.2	5½	277	60	5.3
75	48.5	41.62	5½	300	60	4.9
75	48.5	42.22	5.75	277	60	4.95
100	56	49.25	5.75	300	60	5.4
100	56	49.72	4.50	257	60	5.25
111	62.5	55.72	5.50	225	60	4.46
400	128.5	120.	7	120	60	3.48
500	108	99.35	8.75	150	60	3.06
600	128.5	119	7.50	150	60	3.10
850	128.5	120	12	120	60	2.78
1250	153	144	12	100	60	2.25

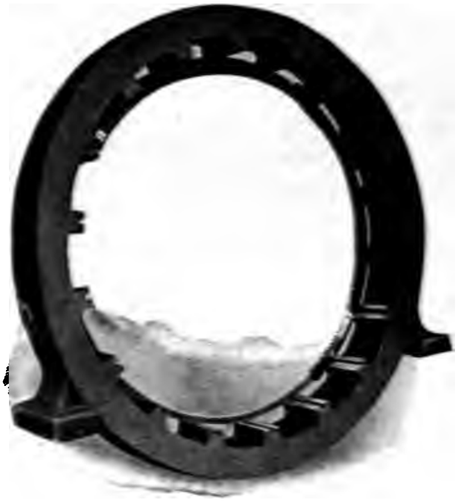


FIG. 31.—Stator Frame, End Plate, Laminations (Westhingouse) .

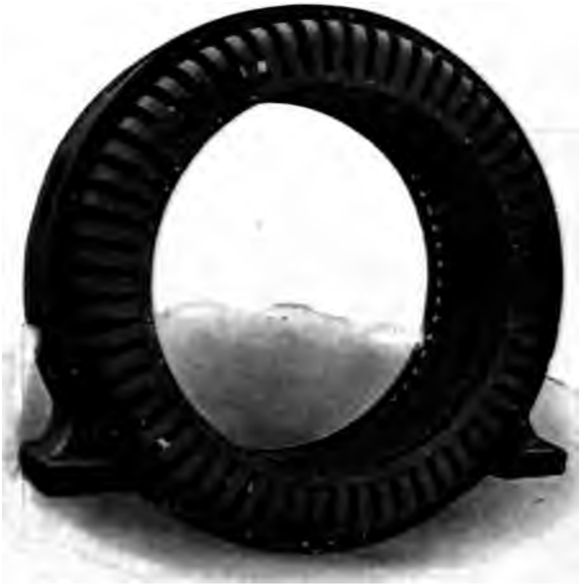


FIG. 32—Engine-type Generator Stator, 75 K.V.A. (Westinghouse).

TABLE X

DIAMETERS, LENGTHS, AND OUTPUT COEFFICIENT FOR LARGE ALTERNATORS

Output, K.V.A.	Outside Diam., Inches.	Inside Diam., Inches.	Length Armature, Inches.	Speed, r.p.m.	Frequency Cycles per Second.	Q
1500	128.5	116.75	18½	225	60	4.55
2000	128.5	117.615	20.5	200	60	3.40
2500	128.5	110.25	20.5	360	60	4.20
3000	128.5	116.75	20.5	300	60	3.40
3000	128.5	117	20.5	240	60	2.72
3600	128.5	110.5	20.5	225	60	2.94
3750	128.5	109	18.5	360	60	2.94
3940	128.5	110.5	20.5	400	40	3.45
12500	182.	128.5	30	300	50	2.38

(E) Number of Inductors

$$Z_t = \frac{(\pi)(D_1)(IC)}{I_a}; \tag{12}$$

where Z_t = total number of armature inductors;
I_a = current in amperes;
D_1 = inside diameter of the armature = the bore;
IC = the product of current and conductors per inch of armature periphery.

The diameter D which we have determined by Eq. (11) is the outside diameter of the laminations. By referring to the several tables in which both inside and outside diameters are given, we can find a machine of approximately the same outside diameter, frequency and speed as the machine under consideration, and from the inside diameter which is given, estimate very closely what the bore of our machine should be. Later on, we may have to increase or decrease it a little, in order to give the armature magnetic circuit the proper sectional area.

IC is in a sense a design coefficient and increases in about the same proportion as Q decreases.

Values of IC for commercial machines are indicated by Tables XI and XII.

TABLE XI

Values of "IC" for High-speed Belted Alternators

Output, K.V.A.	IC.	Output, K.V.A.	IC.
10	200	125	475
25	350	150	500
50	390	175	525
75	415	200	550
100	450	225	590

TABLE XII

Values of "IC" for Engine-type Alternators

Output, K.V.A.	IC.	Output, K.V.A.	IC.
50	450	400	660
100	495	450	675
150	520	500	695
200	560	550	700
250	590	600	705
300	615	1000	710
350	640	5000	725

As an illustration of the above, a certain 3600-K.V.A., 6600-volt, 3-phase, 60-cycle, 225-r.p.m. alternator was calculated as follows: D_1 was 115 inches. The number of armature ampere turns per inch of periphery $= IC$ was assumed as approximately 700. The normal current per phase (open-type star winding) was:

$$I_a = \frac{(3600)(1000)}{(6600)(1.73)} = 316 \text{ amperes.}$$

$$Z_t = \frac{(\pi)(115)(700)}{316} = 800.$$

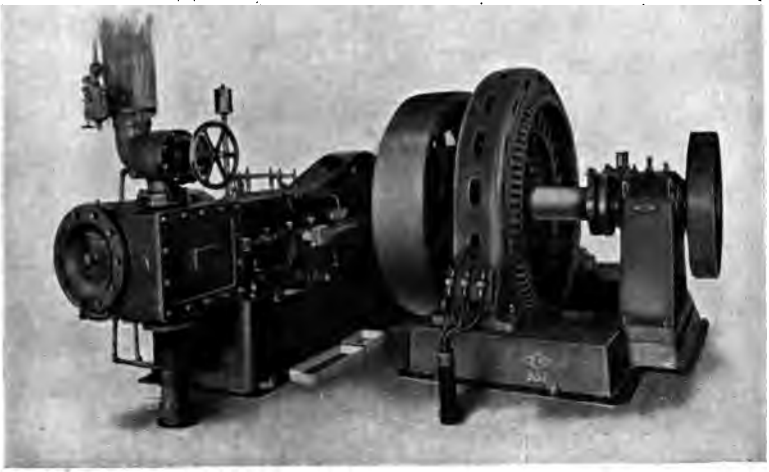


FIG. 33.—High-speed Engine-type Alternator (Electric Machinery Co.).

Next the number of armature slots have to be assumed. There are 32 poles and 3 phases. The total number of slots should be a multiple of the three phases and 32. Assuming 2 slots per pole per phase, the total number of slots is 32 times 2 times 3 = 192 slots; 800 divided by 192 gives the number of conductors per slot. The nearest whole number is 4. The total number of conductors will therefore be 4×192 = 768—instead of 800 as assumed.

(F) Flux

Some years ago air-gap densities of 5000 to 6000 lines of force per square cm. were used. Now it is not unusual to find air-gap densities of from 10,000 to 12,000 lines of force per square cm. for belt-driven and engine-type alternators and up to nearly double this amount for turbine-type alternators. It is desirable that such a value be chosen for the air-gap density as will almost saturate the teeth, but at the same time, it must be remembered that this also tends to increase the leakage. Tables XIII and XIV are given as a guide:

TABLE XIII

AIR-GAP DENSITIES IN GAUSSES, 25-CYCLE ALTERNATORS, BELTED OR ENGINE TYPE

K.V.A. Capacity.	Density, Lines per Sq. Cm.	K.V.A. Capacity	Density, Lines per Sq. Cm.
10	6000	2000	10000
50	7000	3000	10500
100	8000	4000	10800
300	8500	5000	11000
500	9000	10000	12000
1000	9500		

TABLE XIV

AIR-GAP DENSITIES, IN GAUSSES, 60-CYCLE ALTERNATORS, BELTED OR ENGINE TYPE

K.V.A. Capacity.	Density, Lines per Sq. Cm.	K.V.A. Capacity.	Density, Lines per Sq. Cm.
10	4500	2000	7500
50	5200	3000	7900
100	6000	4000	8200
300	6400	5000	8500
500	6750	10000	9000
1000	7100		

We have determined the frequency and the total number of conductors. The flux ϕ, for no load, is now determined from the formula:

$$E_a = \frac{(K)(\phi)(f)(Z)}{10^8 a}, \tag{13}$$

where ϕ = flux per pole at no load and K, f, Z and a have the same significance as assigned in Chapter I.

It is suggested that ϕ be calculated for a value of E_a, that is, in from 5 to 8 per cent in excess of the normal no-load voltage, so that ϕ as calculated for no load will approximate quite closely the actual flux per pole at normal load, and with normal terminal voltage.

Knowing the flux, we next determine:

(G) Breadth and Circumferential Width of Pole

$$W_2 = \frac{\phi}{WB}, \tag{14}$$

where ϕ = flux per pole;
B = no-load air-gap density (see Tables XIII and XIV);
W = breadth of pole; usually is equal to the length of the armature laminations, therefore usually is equal to L;
W_2 = circumferential width of pole.

W_2 = should come out not less than 55 per cent or more than, say, 72 per cent of the pole pitch. Otherwise it will be necessary to keep readjusting our calculations until a value within these limits is attained.

While W should be equal to L the pole may be a little narrower than the length of the armature, if it is necessary.

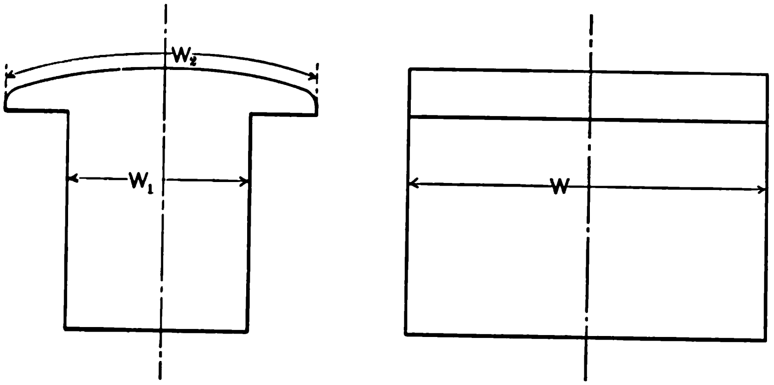


FIG. 34.

About the proportion shown in the following figure is sometimes used.

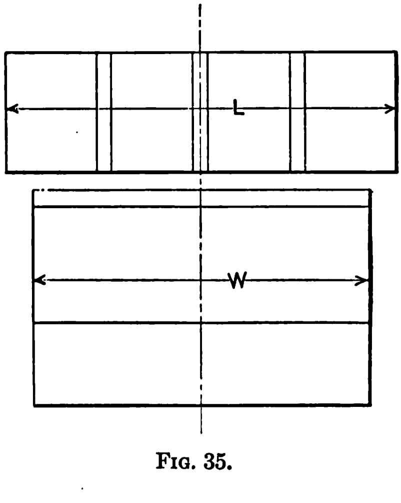


FIG. 35.

We have assumed so far that we have a sinusoidal distribution of the flux. This is not quite true in actual machines, but is usually so very close that it will not greatly affect the results of our work, as to the E.M.F. and number of inductors, except in special cases. It is, however, very important that we determine the field and voltage forms, as a bad wave form is often very undesirable.

(H) Determination of Field and Voltage Forms

The author is indebted to an engineer formerly employed by the Westinghouse Company for the following method of determining the field form:

Draw two adjacent poles to any convenient scale, or rather just one pole as indicated in Fig. 36. Divide the pole pitch into 24 equal parts. Let S be the air-gap at the center of thc pole. Let b_x be the mean width of a tube of force, and S_x its mean length. The magnetic conductivity is proportioned to b_x/S_x. The field density on the armature surface is proportioned to

$$\frac{b_x}{A_x S_x}.$$

Let the maximum field density under the pole be 100. Use S as unity in measuring S_x. The density B_x at any point X would be

$$B_x = 100 \frac{1}{S_x} \frac{b_x}{A_x}.$$

Since in most cases $\frac{b_x}{A_x}$ is practically equal to unity, it is sufficiently accurate to measure the length of the central

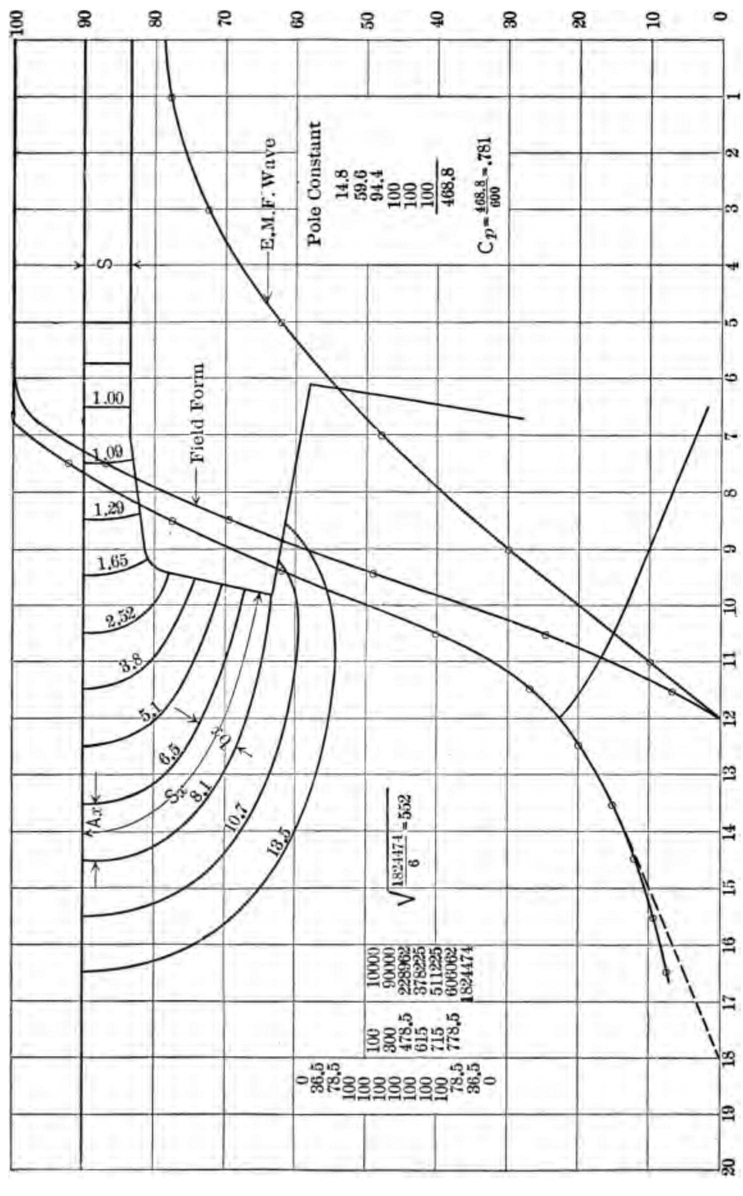


FIG. 36.—Illustrating Method of Determining Field Form and E.M.F. Wave Form.

line of force in the tube in the units of S and make the field density B_x inversely proportional to this length.

$$B_x = \frac{100}{S_x}.$$

With this construction we can plot the field form of one pole's magnetic flux in the percentage of maximum density. As the fluxes of adjacent poles of opposite polarity are superposed on each other, the actual field form is obtained by subtracting the field densities of the two poles where they overlap. The method of construction is indicated by Fig. 36.

Let C_p = the pole constant, then (see Fig. 37)

$$C_p = \frac{\text{area enclosed by the actual field form}}{\text{area rectangle } ABCD}.$$

$$C_p = \frac{\int_0^{\frac{\alpha}{2}} B_x d\alpha}{\frac{\alpha}{2} B_{\text{max.}}}.$$

Also

$$B_{\text{av.}} = \frac{\int_0^{\frac{\alpha}{2}} B_x d\alpha}{\frac{\alpha}{2}},$$

therefore

$$C_p = \frac{B_{\text{av.}}}{B_{\text{max.}}}.$$

In the actual construction as in Fig. 36 we usually divide the base line into six equal divisions, and then take the average of the six middle ordinates in order to get $B_{av.}$ C, for a sine wave is equal to 1 divided by $\frac{\pi}{2}$, or is equal to .637.

E.M.F. Wave Form. The wave form of E.M.F. induced in the armature through the relative motion of the field and conductors can be constructed from the field form. The E.M.F. wave induced in each single conductor is exactly of the same shape as the field form itself. For more than one conductor, the resultant will be the sum of the values, therefore the resultant form of E.M.F. wave depends on the number and distribution of conductors forming one group or winding element.

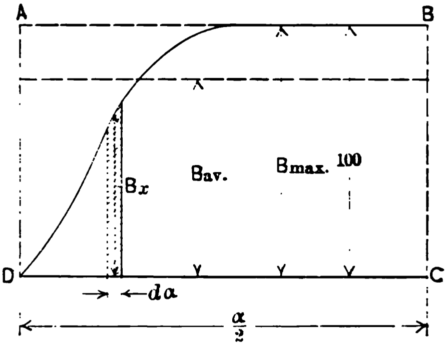


FIG. 37.

It can be shown that if there are six or more slots per pole the wave form is practically independent of the number of conductors, that is, it may be constructed by using any convenient number. Twelve is a very convenient number to use. This gives 4 slots per pole per phase for three phase and six slots per hole per phase for two-phase machines. In single-phase machines it is usual to take into consideration the actual distribution of conductors.

The fundamental idea of construction is that we move the group of conductors in the magnetic field and determine the number of lines of force each conductor cuts. Adding these figures with their respective plus or minus signs, we obtain a value proportional to the E.M.F. induced in the whole group of conductors. In Fig. 36 is shown the construction for a three-phase alternator, assuming twelve slots or conductors per pole, and an open-type star winding. Eight conductors one-twelfth of a pole pitch apart are therefore assumed.

A study of Fig. 36 will very quickly show how the E.M.F. wave was constructed for this particular machine. The values of the E.M.F. are relative values only, and are expressed in terms of magnetic field density. The max. value of the E.M.F. wave shown in Fig. 36 is 778 and the square root of the mean squared value is 552; 552 divided by 778 gives us .702 (.707 is the value for a sine wave), hence we see that the E.M.F. wave approaches very closely to a sine wave, even though the field form does not.

The case considered above should give the designer an understanding of the fundamental ideas of the procedure, so that for any given machine under consideration he can devise his own method of constructing the E.M.F. wave from the field form. *He should keep changing the shape of the pole, if necessary, until one is obtained that will produce, very closely, a sine wave.*

The author's attention was recently called to an alternator in which the ninth harmonic was very pronounced. The machine had nine slots per pole, or three slots per pole per phase. Open slots were used, and the pole covered such a percentage of the armature surface that at one instant there would be six teeth and five slots under a pole, whereas at the next instant there would be five teeth and six slots. Furthermore, the air-gap was of uniform width. The result was that the magnetic reluctance and hence the field strength varied considerably with the position of pole wheel. The result of course was very pronounced tooth harmonics. If a gradually increasing air-gap from the center of the pole toward each edge were employed, the tooth harmonics would probably have been avoided. *We ought therefore to draw the field form with the pole in several different positions with respect to the armature, and make the pole of such a shape that we get the same strength of field for the various positions.*

Coefficient of Chording.—The chording of the winding reduces the number of effective conductors in the ratio of the sine of one-half the electrical degrees between the two sides of the coil, or,

$$X = \sin \frac{\delta}{2},$$

where X = coefficient of chording,

δ = angle between two sides of coil. (See Fig. 38).

(I) Number of Slots

The number of slots per pole for two- and three-phase machines must be divisible by the number of phases, and when the same stampings are to be used for both two- and three-phase machines, the number of slots per pole must be divisible by six. This means either six or twelve slots. Six are used unless the K.V.A. per pole are very high. On three-phase machines either six or nine slots per pole are usually used.

Slots may be divided into three classes:

1. Open slots;
2. Partially closed slots;
3. Closed slots.

Open slots permit the use of machine-wound coils, hence the coils may be entirely insulated before placing them in the slots. The self-induction due to slot leakage is of course less. There are more likely to be tooth harmonics introduced into the E.M.F. wave form. The air-gap is somewhat less than in the case of closed or partially closed slots.

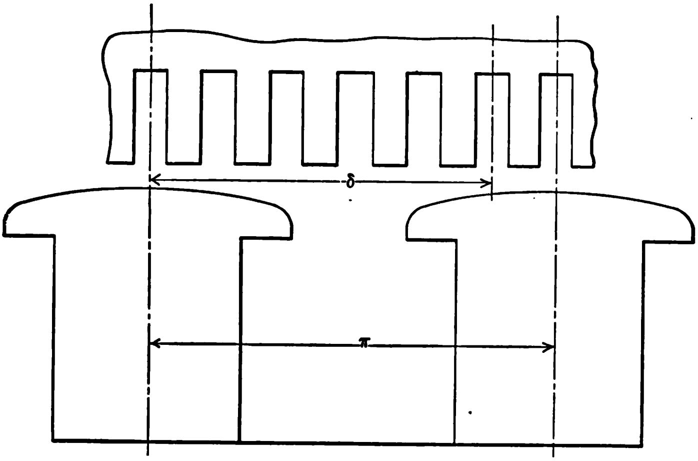


FIG. 38.

Partially closed slots require a great deal of care in construction. They decrease the magnetic reluctance, and the possibility of tooth harmonics is much reduced. The principal objection to partially closed or closed slots is, of course, the poorer regulation.

As the number of slots is increased the cost of the shop work is increased. Filing of slots should be avoided as much as possible, therefore the additional allowance made in slot width for filing becomes more important as the dimensions of the slots are made smaller by increasing their number.

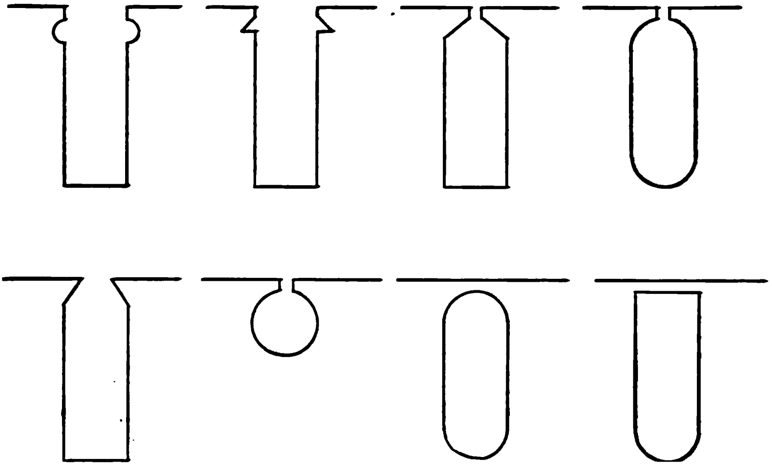


FIG. 39.—Illustrating Various Forms of Armature Slots.

(J) Dimensions of Armature Inductors

Find the required dimensions of the armature inductors from the following formula:

$$(15) \qquad A_w = \frac{I_a}{k},$$

where A_w = area in square inches of armature inductor;
I_a = current in amperes in each winding element;
k = current density in amperes per square inch.

For high-speed well-ventilated machines, $k = 2200$ to 2500; for low-speed well-ventilated machines, $k = 1800$ to 2200.

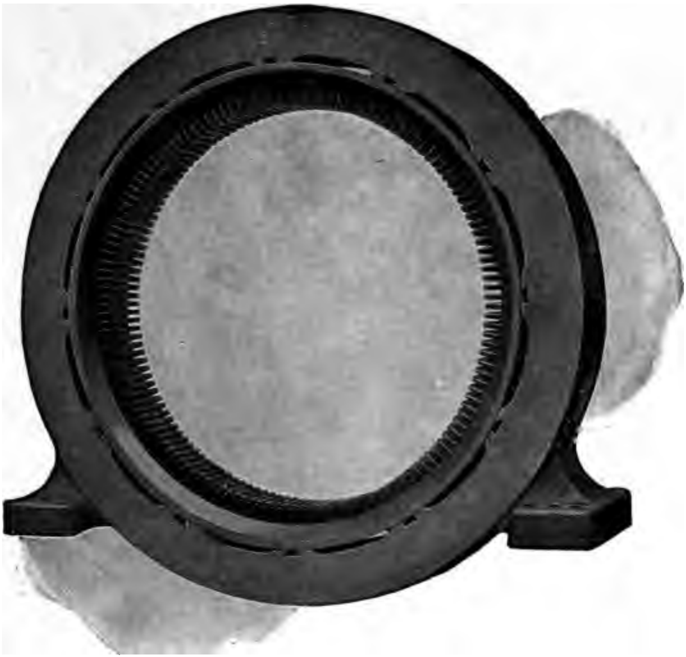


FIG. 40.—Stator with Assembled Core (Westinghouse).

(K) Insulation of Armature Inductors

The insulation of the armature coils is one of the most critical features of an alternator. The problem is much the same as in direct-current armatures, except that the voltages are often much higher. In order to obtain as high a space factor as possible in the armature slots, it is essential to select the very best materials. Careful attention should also be given to the order of arrangement of the insulating materials, so that those which are strong dielectrically but weak mechanically are protected by those suitable for withstanding mechanical strains.

For slot linings, such materials as presspahn, leatheroid, horn fiber, red rope paper, and manilla paper are suitable. Great care must be taken to subject all slot-linings to thorough drying and waterproofing processes. One very effective process is to subject them to prolonged soaking in hot linseed oil.

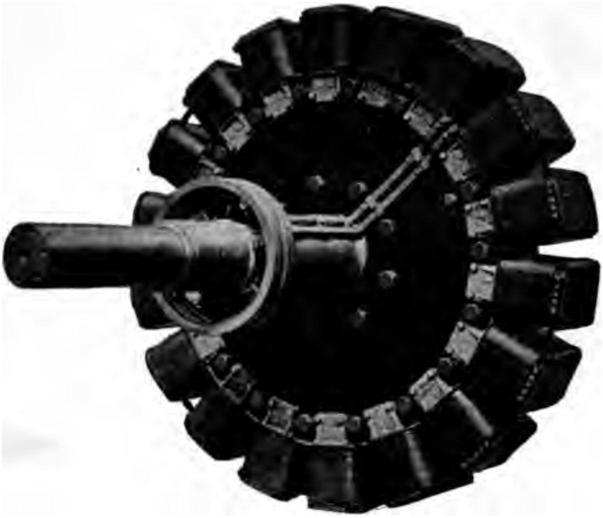


FIG. 41.—Rolled Steel Plate Spider with Field Coils Assembled (Westinghouse).

Mica and micanite should be used for slot linings in high-voltage machines only. For materials to be used to bind the conductors together into coils, there are several available, as for example cotton tape, linen tape, treated cloth tape, or cambric treated with one of various kinds of varnishes, impregnated manila paper, mica paper, oiled unbleached cotton, or a cotton covering acting as a skeleton for any one of several varnishes. The insulation around the individual conductors in no case should be less than a double cotton covering, and it should be filled with a good insulating varnish.

For further information see Turner and Hobart's book on " The Insulation of Electric Machines."

The width of a slot is generally made about equal to the width of a tooth, and its depth from two to three and one-half times its width. The magnetic density in the teeth must not tend to oversaturate them, but on the other hand should nearly saturate them so as to prevent a shifting of the lines of force as the pole approaches and leaves a tooth.

In order to get the average length of one turn lay off the armature coil to scale on a drawing board. An even number of slots per pole per phase will give coils all of which are interchangeable, so that only one mold is required. The use of this coil is practically limited to armatures having open slots. It is illustrated by Fig. 42.

The coils shown in Fig. 43 are simpler in shape but there are as many different forms required as there are coils per pole per phase.

Calculate the length of conductor in each coil. The total length of conductor in each phase will then be the number of coils in that phase times the length of conductor in each coil. This resistance, R_a', will be the resistance of one phase. For a three-phase star-connected winding, the resistance, R_a, between adjacent slip rings would be twice R_a', etc.

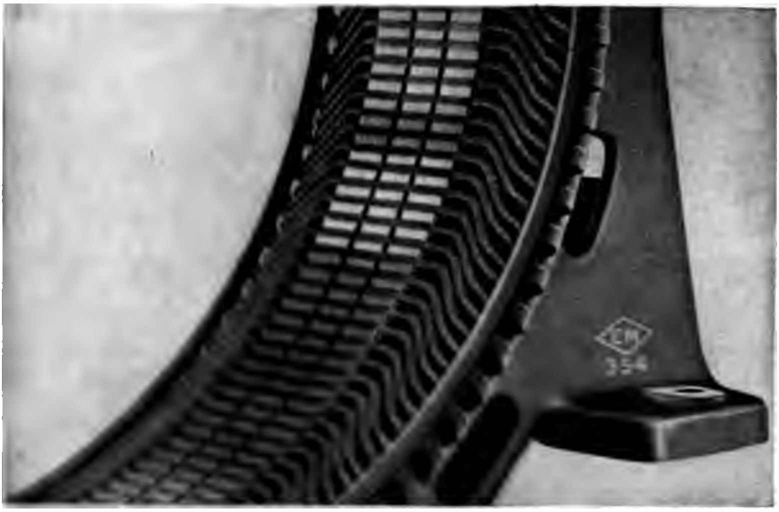


Fig. 12. Interchangeable Armature Coils (Electric Machinery Co.).

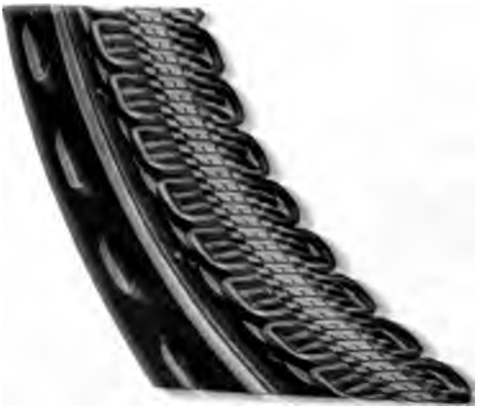


Fig. 13. Non-interchangeable Armature Coils.

The heat loss in each phase of the armature will be $I_a^2R_a'$ where I_a is the current in each phase. For two phase the total I^2R loss will be (2) $(I_a^2R_a')$; for three phase, (3) $(I_a^2R_a')$, etc.

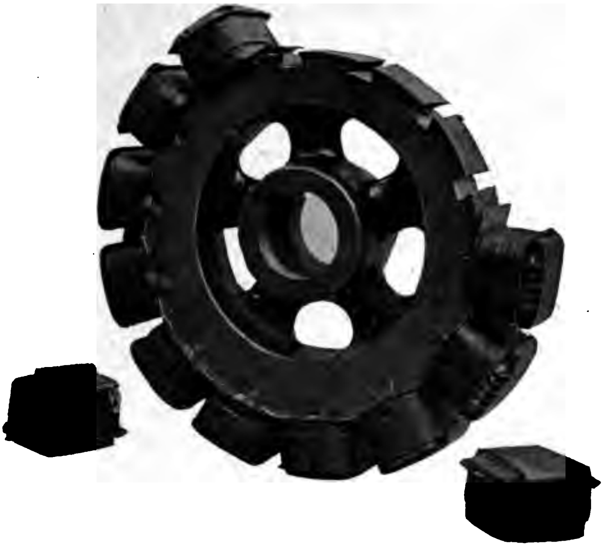


FIG. 44.—Cast Spider, Dovetailed Pole (Westinghouse).

(L) Iron Losses in the Armature

(16) $$A_c = \frac{\phi}{2B_c},$$

where A_c = cross-section of the armature core below the teeth;
B_c = magnetic density in the core below the teeth;
ϕ = useful flux per pole (actual flux minus the leakage).

(17) Depth of core below teeth $= \frac{A_c}{L}$,

where L = length of armature laminations + (insulation + ventilating ducts).

For 25-cycle alternators, B_c should not exceed from 70,000 to 75,000 lines of force per square inch; for 60-cycle machines it should not exceed from 45,000 to 55,000. A density of from 100,000 to 110,000 is usually employed in the teeth, and from 85,000 to 95,000 lines of force per square inch in the pole cores.

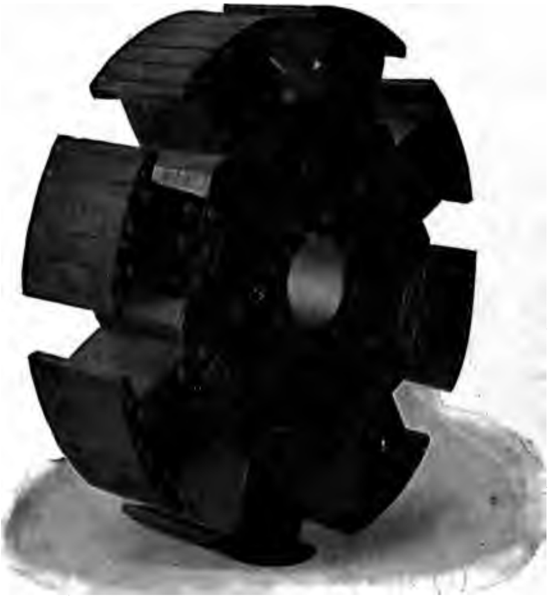


FIG. 45.—Rotor Core with Pole Pieces Assembled on Spider (Westinghouse).

The length and width of the teeth, the area of the core, and the area of the core below the teeth and the length of the armature being known, the volume of the core in cubic inches may be calculated.

$$(18) \qquad W_c = (V_c)(.277);$$

where W_c = weight of core in lbs.;
V_c = volume of core in cu.in.

There are two sources of iron losses in the armature. These sources are, first, the energy spent in continually reversing the magnetism in the armature core as the armature revolves. It is called hysteresis. Second, that used in setting up useless currents in the iron. It is called eddy current loss.

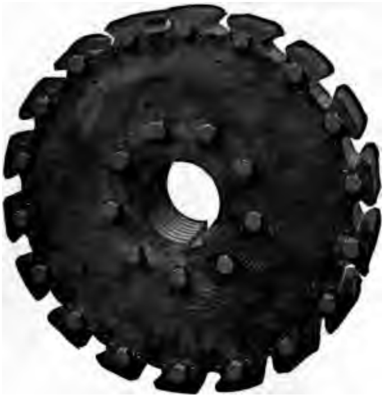


Fig. 46.—A Rolled Steel Plate Spider (Westinghouse).

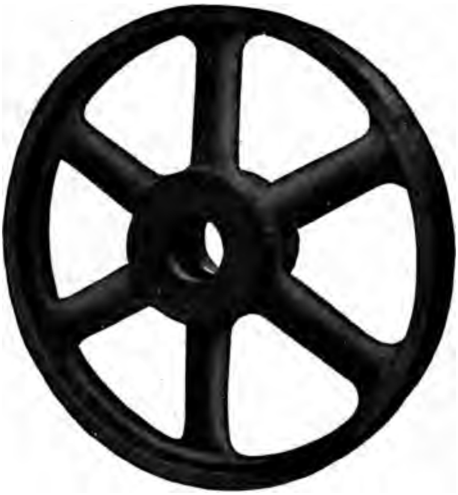


Fig. 47.—A Cast-steel Spider (Westinghouse).

Although a number of very eminent scientists worked for years on the problem of hysteresis, it remained for an engineer of our time to establish the laws. In 1892 Mr. C. P. Steinmetz gave out the results of his experiments, showing that the energy dissipated by hysteresis varies directly as the frequency of the reversals, directly as the total mass of iron, and approximately, as the 1.6 power of the magnetic density. This law he expressed by the following empirical formula:

$$P_h = \mu B^{1.6} f V: \tag{19}$$

where P_h = hysteresis loss in ergs;
μ = coefficient of hysteresis;
f = frequency in cycles per second;
V = volume of iron in cu.cm.

The coefficient of hysteresis depends upon the physical and chemical qualities of the iron. For good armature iron it varies from .0012 to .0020. A fair value for good iron is .0015.

Reducing to practical units and inserting .0015 for μ we get,

$$P_c = \frac{(1.24)(B_c^{1.6})(f)(V_c)}{10^{10}}; \tag{20}$$

where P_c = hysteresis loss in the portion of the armature below the teeth;
B_c = magnetic density in lines per sq.in.;
V_c = volume in cubic inches;
f = frequency in cycles per sec.

$$P_t = \frac{1.24 B_t^{1.6} f V_t}{10^{10}}; \tag{21}$$

where P_t = hysteresis loss in watts in the teeth;
B_t = average density in the teeth;
V_t = volume of the teeth.

$$P_a = P_c + P_t, \tag{22}$$

where P_a = total hysteresis loss in the armature.

From his experiments, Steinmetz also found that the energy consumed by eddy currents induced in a body of iron varies as the square of the magnetic density, as the square of the frequency and in direct proportion to the volume of the iron. This he expressed by the following empirical formula:

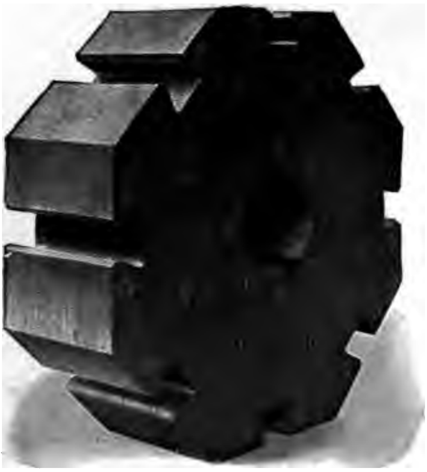


FIG. 48.—Laminated Steel Spider (Westinghouse).

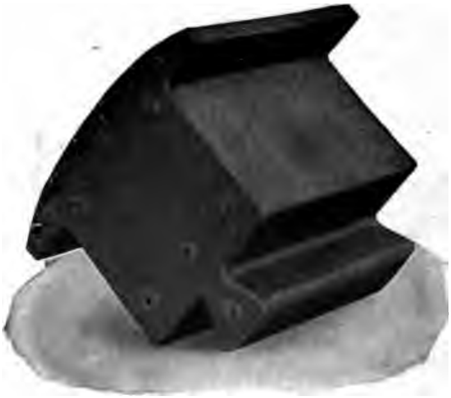


FIG. 49.—Pole Piece Showing Dovetail Projection (Westinghouse).

$$P_e = (\eta)(B)^2(f)^2(V), \tag{23}$$

where P_e = eddy current loss in ergs;
η = eddy current constant,

depending upon the thickness and the specific electrical conductance of the material. For the numerical value of this constant Steinmetz gives the following formula:

$$\eta = \frac{\pi^2}{6} d^2 Y 10^{-9} = 1.645 d^2 Y 10^{-9}; \tag{24}$$

where d = thickness of iron laminæ in cm.
Y = electrical conductivity in mhos;
Y = 100,000 for ordinary armature iron.

Inserting the value of η with reference to iron and reducing to practical units the following formula is obtained:

$$P_c' = \frac{(4.2)(d^2)(B_c)^2(f)^2V_c}{10^{11}}, \tag{25}$$

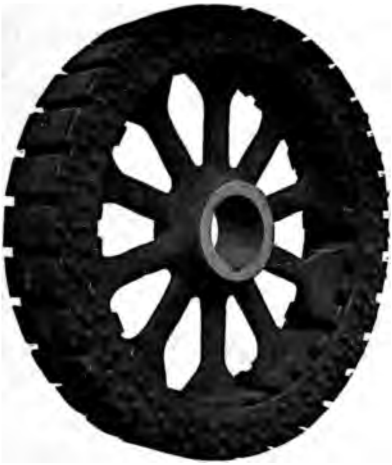


FIG. 50.—Cast Spider, Laminated Rim (Westinghouse).

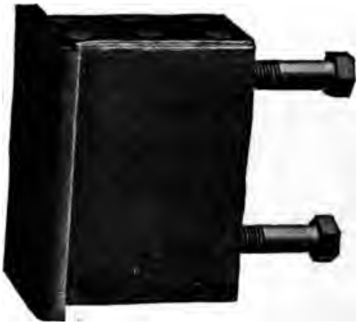


FIG. 51.—Pole Piece with Bolts (Westinghouse).

where P_c' = eddy current loss in that portion of the armature below the teeth in watts;
d = thickness of iron laminations in inches (.014 is a fair value);
B_c = magnetic density in the armature below the teeth;
f = frequency of reversals in cycles per second;
V_c = volume of core below the teeth in cu.in.

$$P_t' = \frac{(4.2)(d^2)(B_t)^2(f)^2(V_t)}{10^{11}}, \tag{26}$$

where P_t' = eddy current loss in the teeth in watts;
B_t = average density in the teeth;
V_t = volume of the teeth in cu.in.

$$P_a' = P_c' + P_t', \tag{27}$$

where P_a' = total eddy current loss in the armature.

$$P_a'' = P_a + P_a', \tag{28}$$

where P_a'' = total iron loss in the armature.

The American Society for Testing Materials have made a number of experimental determinations of the core losses in various armatures and have published curves in their proceedings which show the relationship between the losses per unit volume of the iron and the product of kilo-gausses and frequency. The author believes it is better for the student to work out the losses by means of the above formulas, as he will then get a definite idea as to just how the iron losses are distributed between the various parts of the magnetic circuit, and also just what proportion of them are due to hysteresis and to eddy currents.

(M) Temperature Rise in the Armature

The amount of the total energy consumed in an armature is $I_a^2R_a + P_a''$. The amount of heat liberated depends upon the area of its radiating surface, upon its circumferential velocity, and upon the ratio of radiating area to the pole area.

As a result of a very elaborate series of tests made at Cornell University the following conclusions were drawn. (See Transactions A.I.E.E., Vol. X, page 349.)

1. An increase of the temperature of the armature causes an increased radiation of heat per degree rise in temperature, but the ratio of increase diminishes as the temperature increases, and an increase of the amount of heat generated in the armature increases the temperature of the armature, but less proportionally.

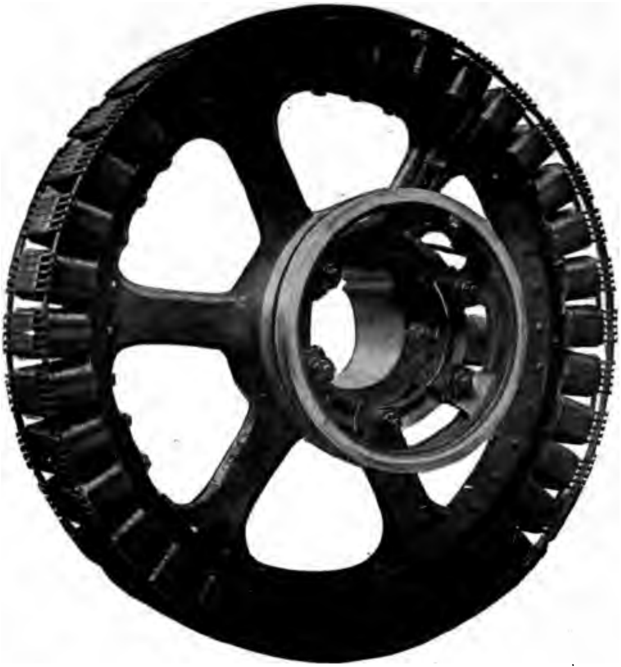


FIG. 52.—Rotor of 200 K.V.A. Sychronous Motor (Westinghouse).

2. An increase in the peripheral velocity increases the amount of heat liberated per degree rise in temperature, but the ratio of increase becomes less with higher speeds.

3. The effect of the field poles is to prevent the radiation of heat.

Mr. Alfred E. Wiener, by combining these results with data and tests of various machines found the values given in Table XV.

TABLE XV

SPECIFIC TEMPERATURE RISE IN ARMATURES

Peripheral velocity in feet per second — V_p.	Temperature rise per unit of energy loss, in degrees C. $= t_a$.					
	Ratio of pole area to total radiating surface.					
	.8	.7	.6	.5	.4	.3
0	110°	100°	95°	90°	86°	83°
10	80	74	70	67	64	62
20	64	61	58	56	54	52
30	55	53	51	49	48	46
40	50	48	47	46	45	44
50	48	47	46	45	44	43
75	47	46	45	44	43	42
100	46	45	44	43	42	41
150	45	44	43	42	41	40

The product of the specific temperature increase and the specific loss gives the rise in temperature.

$$T_a = t_a \frac{P_a'' + I_a^2 R_a}{S_a}, \tag{29}$$

where T_a = rise in temperature of armature in degrees centigrade;

t_a = specific temperature increase;

S_a = total radiating surface of armature in square inches;

$P_a'' + I_a^2 R_a$ = total energy loss in the armature;

$\frac{P_a'' + I_a^2 R_a}{S_a}$ = specific energy loss.

The radiating or cooling surface of an armature is that portion of its superficial area which is in direct contact with the surrounding air. The shape and construction of the armature, and the size and arrangement of the field determine this radiating portion of the armature.

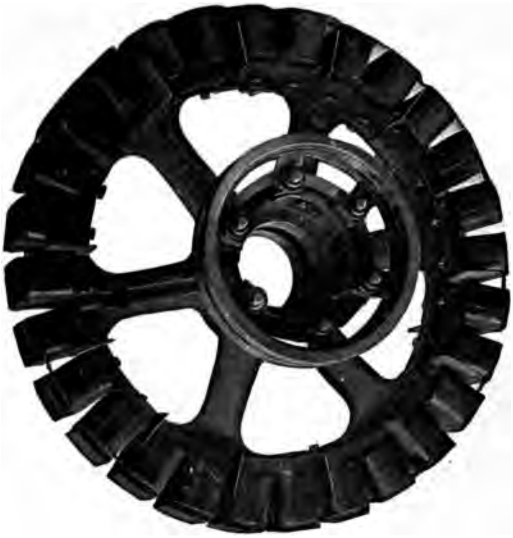


FIG. 53.—Generator Rotor with Collector Rings (Westinghouse).

(30) $$S_a = S + S_1 + S_2 + S_3,$$

where S = external cylindrical surface of the armature in square inches;

S_1 = internal cylindrical surface of the armature core in square inches;

S_2 = radiating surface of the core and conductors at the two ends of the armature;

S_3 = radiating surface presented by one side of a ventilating duct.

$$V_p = \frac{SV + S_1V_1 + S_2V_2 + S_3V_3}{S + S_1 + S_2 + S_3}, \qquad (31)$$

where V_p = average peripheral velocity of the radiating surface of the armature;

V = peripheral velocity of S;

V_1 = peripheral velocity of S_1;

V_2 = peripheral velocity of S_2;

V_3 = peripheral velocity of S_3.

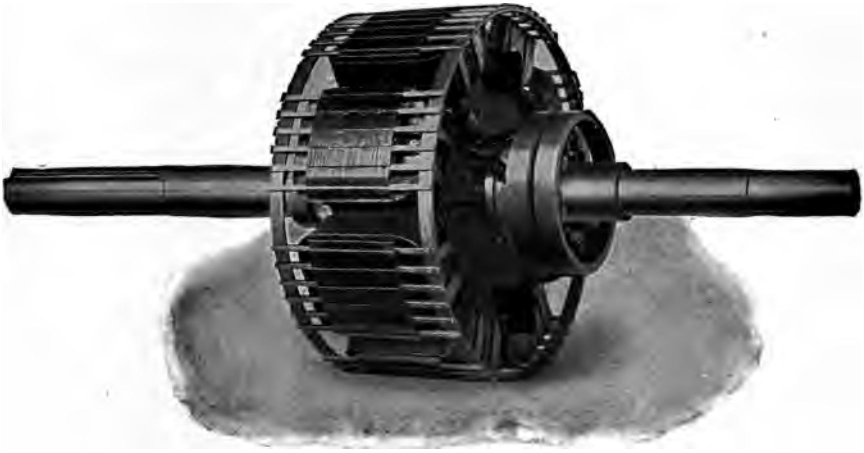


Fig. 54.—Rotor with Squirrel-cage Winding (Westinghouse).

If the temperature rise does not come up to nearly the specified value, the current density in the armature inductors may be increased. If the temperature rise is too high it will be necessary to either increase the area of the armature inductors, or increase the radiating surface by putting in more air ducts or by doing both.

The radiation coefficients of the stationary armature

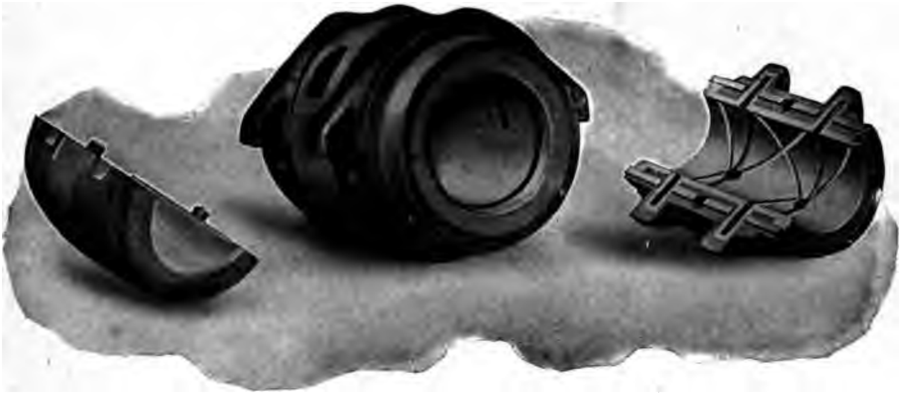


FIG. 55.—Bearings Type G Generators, Rear Bearing and Halves of Collector Side Bearing (Westinghouse).

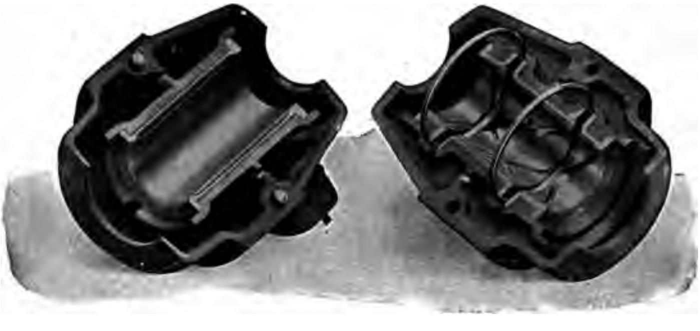


FIG. 56 —Bearing Housing Open, Showing Bearing and Oil Rings, Bracket Type (Westinghouse.)

should be considered as if the armature were revolved, and the field pole held stationary, because of the fact that the poles drive the air through and around the armature at almost the same peripheral velocity that would be obtained were the armature rotated.

(N) Diameter of Shaft

The diameter of the shaft within the core may be found by the formula,

$$D_c' = K_1 \sqrt[4]{\frac{W}{\text{r.p.m.}}}, \tag{32}$$

where W = output of the machine in watts;

K_1 = constant depending on the output of the machine. (See Table XVI.)

TABLE XVI

SHAFT CONSTANTS

Capacity in Kilo-watts.	K_1.	Capacity in Kilo-watts.	K_1.
1	.9	100	1.3
5	1.0	200	1.4
10	1.1	500	1.5
50	1.2	1000	1.6

The diameter of the bearing portion of the shaft may be obtained from the formula:

$$D_b = 0.8 K_1 \sqrt[4]{\frac{W}{\text{r.p.m.}}}, \tag{33}$$

where D_b = diameter of the bearing portion of the shaft in inches.

The length of the bearing may be found from the formula:

$$L_b = K_2 D_b \sqrt{\text{r.p.m.}}, \qquad (34)$$

where L_b = length of the wearing portion of the bearing in inches;

K_2 = constant. (See Table XVII.)

TABLE XVII. (ESTERLINE)

Capacity in Kilo-watts.	K_2 High Speed.	K_2 Low Speed.
1	.075	.100
5	.100	.150
10	.115	.175
50	.125	.200
100	.150	.225
1000	.200	.275

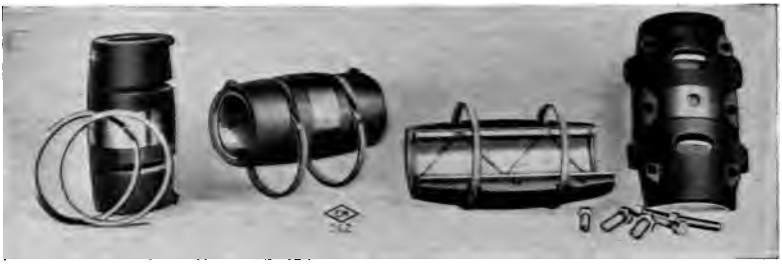


FIG. 57.—Bearings used on High Speed Generators (Electric Machinery Co.).

(O) Cross-section of Pole Core

If ϕ is the flux in the air-gap under one pole at no load, the corresponding full-load value of the flux in the pole core will be:

$$\phi' = \phi\lambda, \qquad (35)$$

where

$$\lambda = \text{leakage coefficient.}$$

λ varies from about 1.15 to 1.40 in modern commercial machines. Ordinarily, 1.25 would be a safe value to use.

Crocker gives the following formula for an approximate determination of the leakage coefficient of revolving field alternators.

$$\lambda = 1 + \frac{(6)(g)(d)}{(a)(m)}, \tag{36}$$

where g = length of air-gap;
d = pole core height;
a = length of pole arc;
m = number of phases.

$$A_p = \frac{\phi'}{B_p}, \tag{37}$$

where A_p = area of pole core;
B_p = magnetic density in the pole core.

The breadth W, may be made equal to the length L, of the armature or a little shorter if desired, then:

$$W_2 = \frac{A_p}{W}. \tag{38}$$

If the core is laminated, an allowance of about 8 per cent should be made for the insulation between laminations. The pole-core density is usually from 65,000 to 85,000 lines of force per square if they are made of cast iron, and from 85,000 to 95,000 if sheet steel is used.

There is not very much difference in the cost of solid and of laminated poles. The advantages of solid poles are:

1. Their damping effect.
2. Can be more reliably fixed on the pole wheel in case of high-speed machines.
3. The section can be made oval is desired, thus giving increased economy in copper.

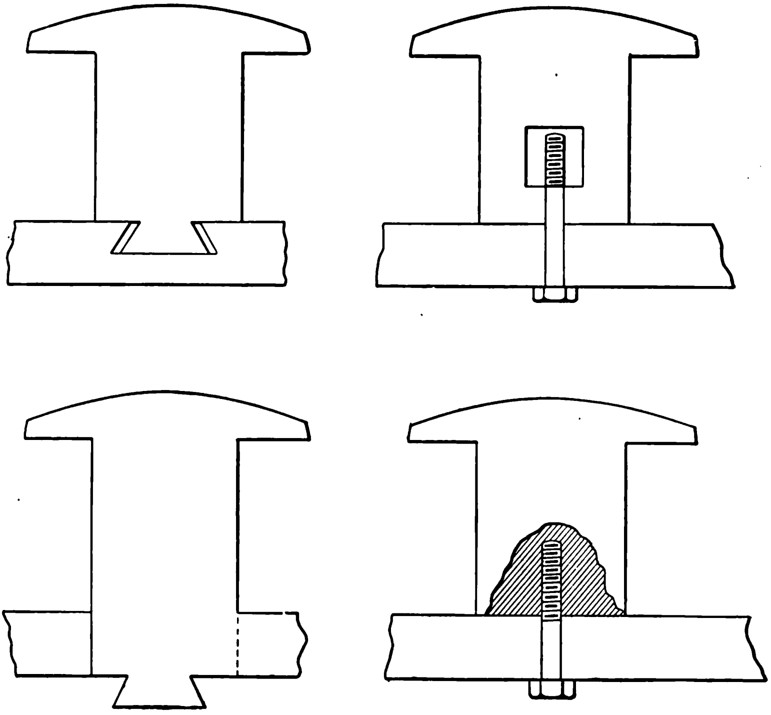


Fig. 58.

With laminated poles, it is easier to perfect the design as regards the shape of the pole piece, and the pole wheel is more apt to run true and keep its shape.

In Fig. 58 is shown different methods of fixing the pole to the pole wheel.

In small machines the pole cores and the magnetic circuit below the pole cores are stamped out of one piece of iron as indicated in Fig. 59.

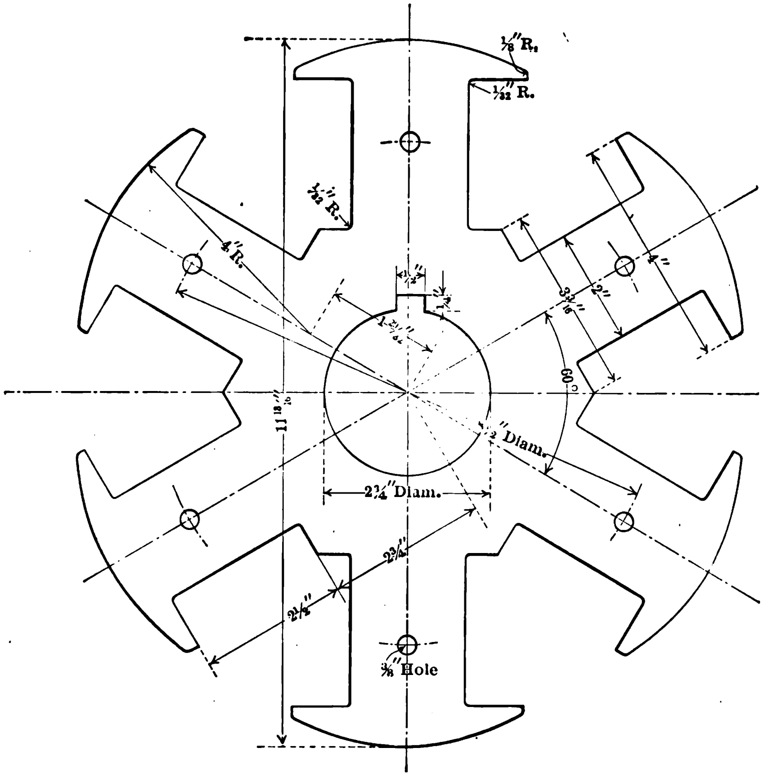


Fig. 59.

(P) Armature Inductance

The armature inductance due to armature reactance should be calculated before the field winding is designed. Since commercial alternators do not have a uniform magnetic reluctance, a perfectly distributed winding, nor a sinusoidal flux distribution, an exact predetermination of the regulation without making any tests is impossible.

The following method of predetermining the armature inductance should give results approximating fairly closely actual results.

The inductance of the slots covered by a pole, and those not so covered will be calculated separately.

The reluctance of the path of the lines of force about one uncovered slot is given by the following formula:

$$R_l = \frac{1}{\frac{dL_a}{2b'} + \frac{d'L_a}{B} + \frac{2wL_a}{A\pi}}, \tag{39}$$

where R_l = reluctance of the flux paths of one slot;
A = tooth pitch in cms.;
w = width of a tooth at the top in cms.;
B = width of a slot at the top in cms.;
d = depth of the coil in the slot;
d' = depth of the slot above the coil;
b = the width of the slot at the bottom;
b' = the width of the tooth at the bottom;
L_a = the length of the armature laminations in cms.

The coefficient of self-induction is numerically equal to the number of lines of force one ampere will produce times the number of turns divided by 10^8, therefore,

$$L_l = \frac{(\phi_l)(t)}{10^8}, \tag{40}$$

where ϕ_l = the number of lines of force produced by one ampere;
t = number of turns in the coil is equal to the number of conductors per slot;
L_l = inductance in henrys,

and

$$\phi_t = \frac{(1.257)(t)}{R_t} \tag{41}$$

To this flux must be added that linked with the end connections of the coil. This varies from 0.45 to 0.75 maxwell per ampere turn per centimeter of the length, L_e, of the end connections.

The average value is usually not far from 0.55, hence,

$$\phi_t = t\left(\frac{1.257}{R_t} + 0.55L_e\right). \tag{42}$$

The minimum value of the inductance will of course occur when the maximum number of slots are uncovered. In a three-phase machine, there may be a time when all the conductors in a winding element would be uncovered. Therefore the minimum inductance would be approximately equal to:

$$L_{\text{min.}} = (L_t)(n)(n'),$$

where L_t = inductance of one uncovered slot;

n = number of slots per pole per phase;

n' = number of winding elements in series, is the number of poles for an open type winding;

$L_{\text{min.}}$ = minimum armature inductance.

For covered slots the inductance will be greater, since the flux passes from the top of a tooth to the pole face, and makes its return circuit through the pole face back to an adjacent slot. The reluctance for a covered slot is:

$$R_t' = \frac{1}{L_a\left(\frac{d}{2b'} + \frac{d'}{B} + \frac{w+A}{4g}\right)}, \tag{43}$$

where L_e = the length of the end connections in cms.;
g = length of air-gap in cms.

The equation for ϕ_l' and L_l' are the same as for the uncovered slots. The maximum inductance is

$$L_{\text{max.}} = (L_l')(n)(n') \tag{44}$$

where L_l' = the inductance for one covered slot.

FIG. 60.—A 6000-K.V.A. 6600-volt, Three-phase, 60-cycle Horizontal Water-wheel Generator (Westinghouse).

The average value $L_{\text{av.}}$, is obtained by multiplying L_{min} by the percentage of the armature which is not covered by the poles and $L_{\text{max.}}$ by the percentage which is. For example if the inductance is 10 henrys assuming all the slots to be uncovered and 15 henrys when they are all covered, and the poles cover two-thirds of the surface of the armature, the average inductance would be, one-third of 10 plus two-thirds of 15 = 13.33 henrys.

The total armature reactance is

$$X_a = 2\pi f L_{av.}. \tag{45}$$

The armature reactance drop is

$$E_2 = I_a X_a, \tag{46}$$

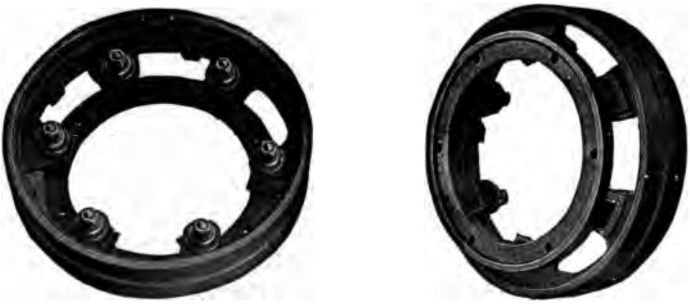

Front. Rear.

FIG. 61.—Collector Rings (Westinghouse).

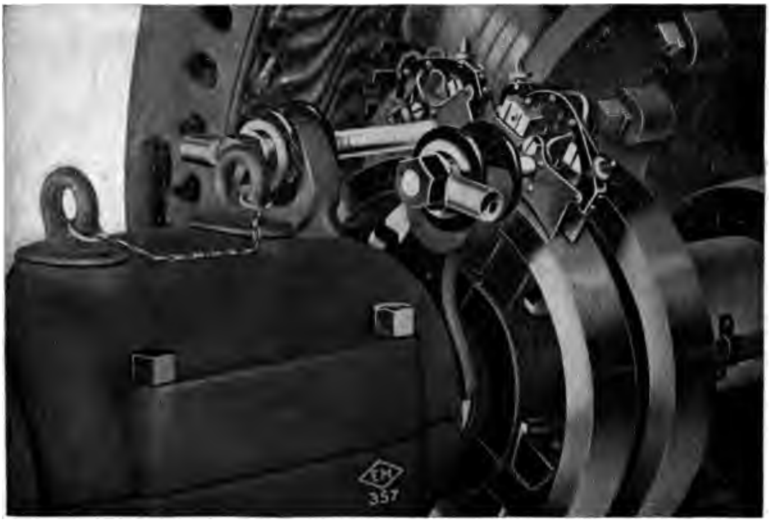


FIG. 62.—Collector Rings, Brush Holders and Supporting Brackets (Electric Machinery Co.).

where E_2 = armature reactance drop per phase (see vector diagram in Chapter I).

X_a = armature reactance per phase,

f = frequency,

$L_{av.}$ = armature inductance.

As an example of the calculation of armature inductance we will take the following:

The dimensions are:

d = 3.60 cms.
A = 4.62 "
g = .50 "
d' = 1.20 "
B = 2.25 "
L_a = 15.00 "
w = 2.50 "
b = 2.00 "

L_e = 45.00 cms.
t = 24
n = 2
n' = 14
f = 60 cycles per sec.
I_a = 30 amperes
E = 2200 volts

The reluctance of the path of the lines of force about one uncovered slot is:

$$R_l = \frac{1}{\frac{(3.60)(15)}{(2)(2)} + \frac{(1.2)(15)}{2.25} + \frac{(2)(2.5)(15)}{(4.62)(\pi)}},$$

$$R_l = .0375 \text{ oersted},$$

$$\phi_l = 24\left[\frac{1.257}{.0375} + (0.55)(45)\right],$$

$$\phi_l = 1398,$$

$$L_l = \frac{(1398)(24)}{10^8} = .000335 \text{ henry},$$

$$L \text{ min.} = (.000335)(2)(14) = .00938 \text{ henry},$$

$$R_l' = \frac{1}{15\left(\frac{3.6}{(2)(2)} + \frac{1.2}{2.25} + \frac{2.5+4.62}{(4)(50)}\right)},$$

$$R_l' = .0133 \text{ oersted},$$

$$\phi_l = 24\left[\frac{1.257}{.0133} + (0.55)(45)\right],$$

$$\phi_l = 2862,$$

$$L_l' = \frac{(2862)(24)}{10^8} = .000687,$$

$$L_{\max} = (.000687)(2)(14) = .0192.$$

The poles cover 65% of the armature, therefore,

$$L_{\text{av.}} = (.65)(.0192) + (.35)(.00938),$$
$$= .01496 \text{ henry}.$$

The armature reactance per phase would be

$$x_2 = (2)(\pi)(60)(.01496),$$
$$x_2 = 5.62 \text{ ohms},$$
$$E_2 = (30)(5.62) = 168.6 \text{ volts}.$$

(Q) Armature Magnetization

The armature reaction in ampere turns may be calculated by means of the formulas given in Chapter I.

These give the result in ampere turns per pair of poles. Since there are as many magnetic circuits as there are poles, and as we usually calculate the number o field ampere turns per pole, it will be found most convenient to divide the results given by these formulas by two, so as to get the armature reaction in ampere turns per pole;

(R) Cross-section of the Wheel Rim

The cross-section of the wheel rim for a multi-polar machine will be

(47 $$A_w = \frac{\phi'}{2B_w},$$

where ϕ' = flux per pole;

B_w = magnetic density in the wheel rim.

FIG. 63.—Brush Holder Bracket Stand (Westinghouse).

If the wheel rim and the pole cores are made of the same material the magnetic density employed in the wheel rim is usually only about 80 to 90 per cent of what it is in the pole core. For a cast-steel wheel rim use 65000 to 75000 lines of force per square inch. For cast iron, from 40000 to 45000.

(S) Air-gap

The air-gap to be used depends very largely upon the required regulation. A long air-gap means more field ampere turns in proportion to the armature ampere turns, therefore better regulation, especially on low power factors. On the other hand, a long air-gap increases the leakage.

As a general rule, about 75 per cent of the field ampere turns should be required to drive the flux through the air-gap. This may require an air-gap as small as one-eighth of an inch, or as large as three-quarters of an inch. For small machines three-sixteenths to three-eighths is common. For large machines it usually lies between three-eighths and three-quarters.

FIG. 64.—Bed Plate for Bracket Type Generator (Westinghouse).

Where good regulation is necessary, it is usually found advisable to make the ratio between the armature and field ampere turns about one to three.

(T) Exciting Ampere Turns

Lay off one of the magnetic circuits on a drawing board to scale, and prepare a table as follows:

Part.	Magnetic Density.	Length of Mean Line.	Ampere Turns per Inch.	Total Ampere Turns.
Arm. core.....				
Teeth.........				
Air-gap.......				
Pole shoe......				
Pole core......				
Wheel rim.....				
Total.........				

As the quantities indicated are obtained insert them in the above table; changes made necessary by further adjustments in the design can quickly and very easily be made by referring back to this table.

The ampere turns may be obtained either from tables or by the following formula:

$$NI_m = \frac{.8\phi_m L_m}{A_m y}, \tag{48}$$

where NI_m = ampere turns necessary to force the flux through the part of the circuit under consideration;
ϕ_m = corresponding number of lines of force;
L_m = mean length in cms.;
A_m = area in sq. cm.;
y = permeability.

If the dimensions are given in inches, then

$$NI_m = \frac{.3133\phi_m L_m}{A_m y}. \tag{49}$$

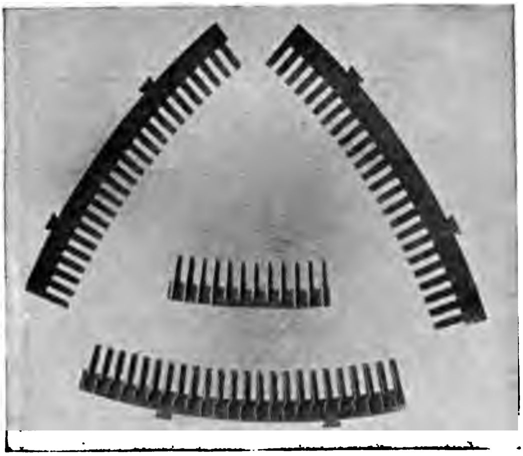


FIG. 65.—Segments of Core Laminations, Finger Plate and Ventilating Finger Plate (Westinghouse).

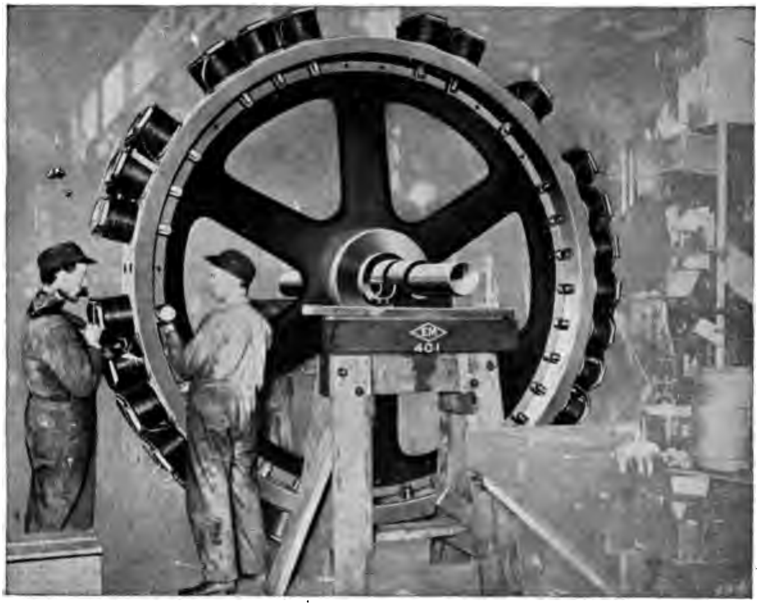


FIG. 66.—Rotor Construction (Electric Machinery Co.).

TABLE XVIII

Permeability of Different Kinds of Iron at Various Magnetizations

Density, Lines per Square Inch.	Annealed Wrought Iron.	Commercial Wrought Iron.	Gray Cast Iron.	Cast Steel.	Sheet Steel.
20000	2600	1800	850	2500	2400
25000	2900	2000	800	2600	2500
30000	3000	2100	600	2750	2625
35000	2950	2150	400	2700	2750
40000	2900	2130	250	2650	2860
45000	2800	2100	140	2600	2975
50000	2650	2050	110	2475	3100
55000	2500	1880	90	2300	3000
60000	2300	1850	70	2100	2900
65000	2100	1700	50	1800	2775
70000	1800	1550	35	1475	2660
75000	1500	1400	25	1160	2500
80000	1200	1250	20	1000	2400
85000	1000	1100	15	850	1900
90000	800	900	12	750	1400
95000	530	680	10	690	1100
100000	360	500	9	590	900
105000	260	350	...	525	480
110000	180	260	...	475	310
115000	120	190	...	425	178
120000	80	150	...	390	145
125000	50	120	...	350	99
130000	30	100	...	250	69
135000	20	85	...	150	40
140000	15	75	...	100	20

By means of the above equations find the number of ampere turns required to force the no-load flux through

1. The armature core;
2. The teeth;
3. The air-gap;
4. The pole shoe;
5. The pole core;
6. The wheel rim.

Add these together, thus obtaining the number of no-load ampere turns per pole.

In order to have plenty margin on low-power factors, the field voltage required at no load should not be more than 50 per cent of the exciter voltage. If a 110-volt exciter is used, the required exciter voltage at no load should be

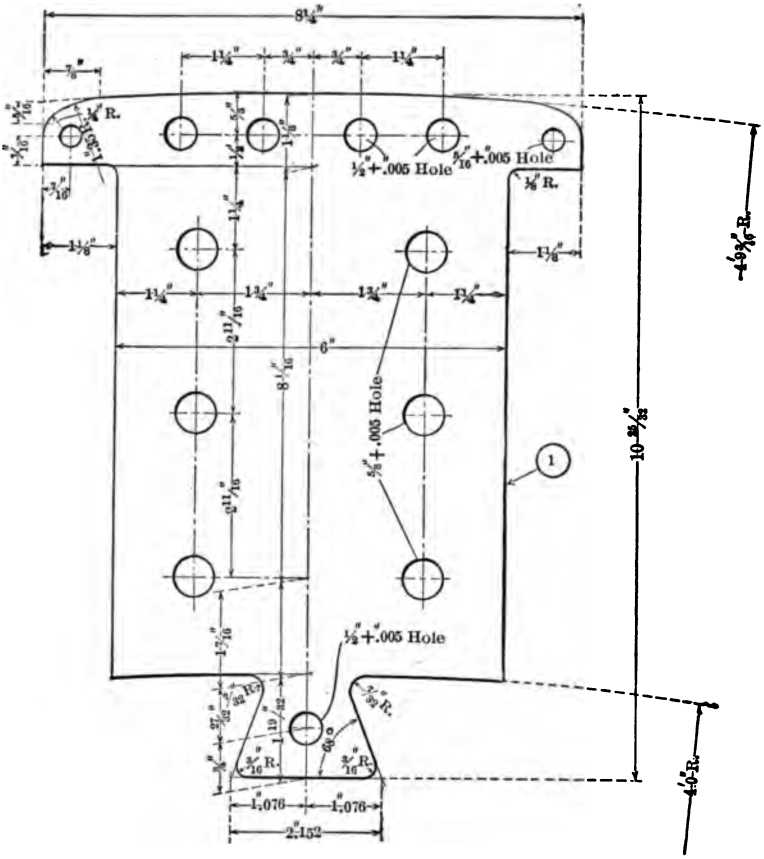


FIG. 67.—Pole Piece of a Large Generator (Westinghouse).

taken as 55 volts. For a 220-volt exciter this value may be doubled. Then for a 110-volt exciter, the E.M.F. per pole would be 55 divided by the number of poles, or,

$$E_f = \frac{E_e}{p}, \tag{50}$$

where E_f = E.M.F. per pole;
p = number of poles;
E_e = E.M.F. of exciter.

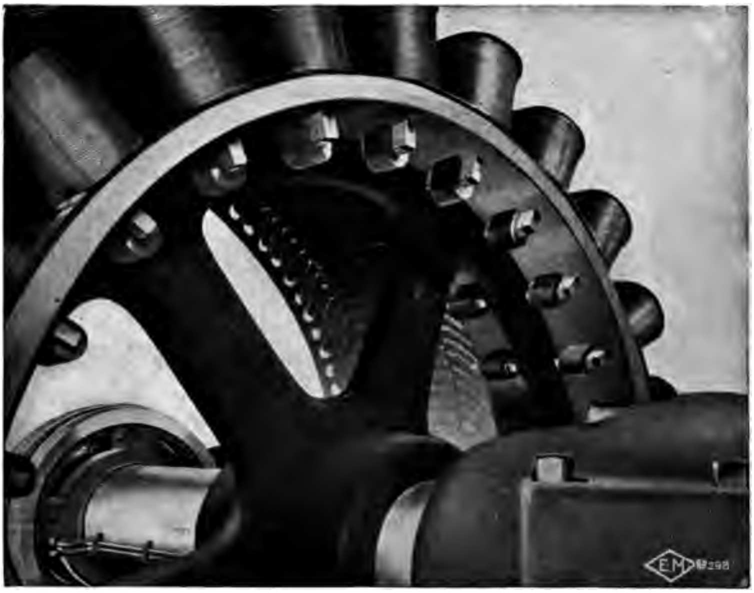


Fig. 68.—Illustrating Method of Fastening Field Coils (Electric Machinery Co.).

For the first trial, get the capacity of the exciter by multiplying the average of the per cent limits given in Table XIX by the capacity of the alternator. The current in the field coils will then be this capacity in watts divided by the normal voltage of the exciter. The resistance of the field coils should then be kept down to such a point that only about one-half the exciter voltage is required to supply the required field current at no load.

Assume what you consider is a reasonable depth of field winding after consulting other designs, and calculate the length of a mean turn. Allow about 1200 circular mils per ampere, select such a size wire, that it will have a resistance R_f that will permit a current to flow that will give the required number of ampere turns when the current is multiplied by the number of turns which can be accommodated in the space available. If the circular mils per ampere are in the neighborhood of 1200, the temperature rise will probably come out about right. Different sizes of wire will have to be tried, and the space available for accommodating the winding may have to be changed in order to accommodate the required number of turns. Since we have allowed 1200 circular mils per ampere, at no load, the current density will probably not exceed 800 circular mils per ampere at full load, therefore should be liberally enough designed.

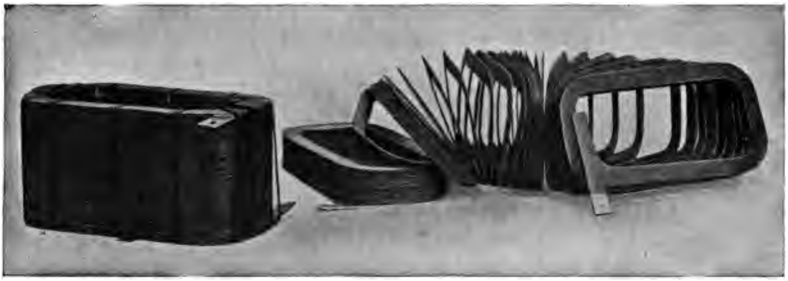


FIG. 69.—Edge Wound Strap Field Coil (Westinghouse).

Check the field coil for temperature rise by the following formula, which is based on Timmerman's experiments, at Cornell University. (See Trans. A.I.E.E., page 342, Vol. X.)

$$T_s = \frac{83 W_p}{S_p}, \tag{51}$$

where T_s = temperature rise of the field coil in degrees C.;
W_p = loss per pole in watts;
S_p = total radiating surface, of the coil in square inches;

T_s should not exceed approximately 20° C. at no load. After the regulation has been determined, T_s should again be calculated for the field amperes required at full load, and 80 per cent power factor and should not exceed 40° C.

The usual limits of the excitation losses is indicated by the following table:

TABLE XIX

EXCITATION LIMITS OF ALTERNATORS

Output of Alternator in K.V.A.	Usual Limits in Per Cent.	Output of Alternator in K.V.A.	Usual Limits in Per Cent.
10	2.00 to 5.00	500	.55 " 2.25
50	1.75 to 4.00	750	.50 " 2.00
100	1.25 to 3.75	1000	.50 " 1.75
200	1.10 " 3.00	5000	.45 " 1.50
300	.85 " 2.65	10000	.40 " 1.25
400	.60 " 2.50		

(U) Field Loss

The watts lost in the field coils will be:

(52) $$W_f = I_f^2 R_f,$$

where W_f = field loss in watts;
I_f = current in field;
R_f = resistance of field winding.

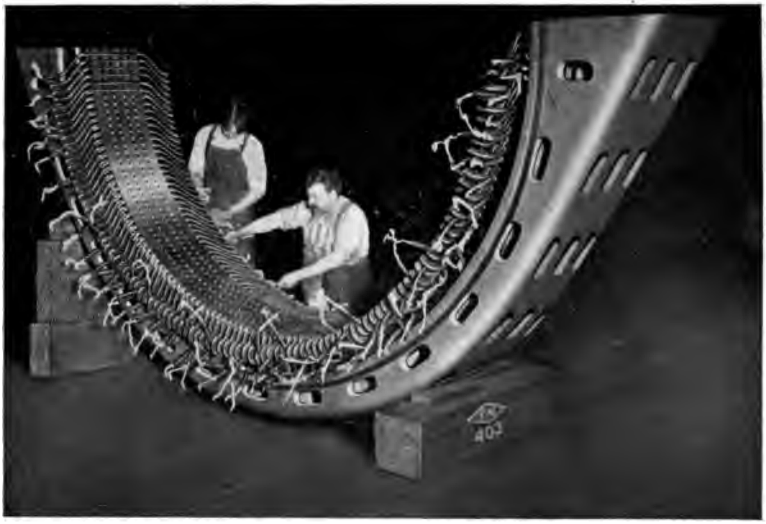


Fig. 70.—Illustrating Armature Winding having Interchangeable Coils (Electric Machinery Co.).

(V) Regulation

The E.M.F., E_1, which in the vector diagram in Chapter I represented the effect of armature reaction, is the E.M.F. which we would have if the ampere turns of the armature only were the magnetizing force. Therefore E_1 may be calculated by substituting in the formula for the E.M.F. of the machine, the value of ϕ that would be produced if the magnetizing force were the number of ampere turns in the armature winding only. Since this flux is always combined with the flux produced by the field, the permeabilities used should be those which correspond to full load conditions. By referring back to the table under the heading, Exciting Ampere Turns, we can quickly and easily get the flux by using the information given in this table. We now know all the components of the vector diagram of electromotive forces. Calculate E_a for normal E.M.F. at the terminals of the machine as per the above diagram. (Fig. 71.)

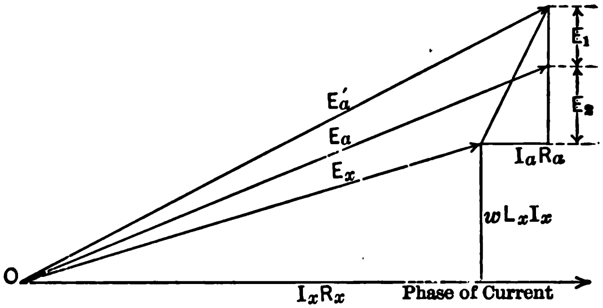


FIG. 71.

Calculate what field current will be required to produce the E.M.F. E_a, also the E.M.F. E_a', that this field current would produce if the load were all thrown off. The regulation in per cent will then be:

$$\text{(53)} \qquad \text{Regulation} = \left(\frac{E_a' - E_x}{E_x}\right)100,$$

where E_x = normal terminal E.M.F.;

E_a' = E.M.F. that would be produced at no load by the field current required to give E_x when the machine is loaded.

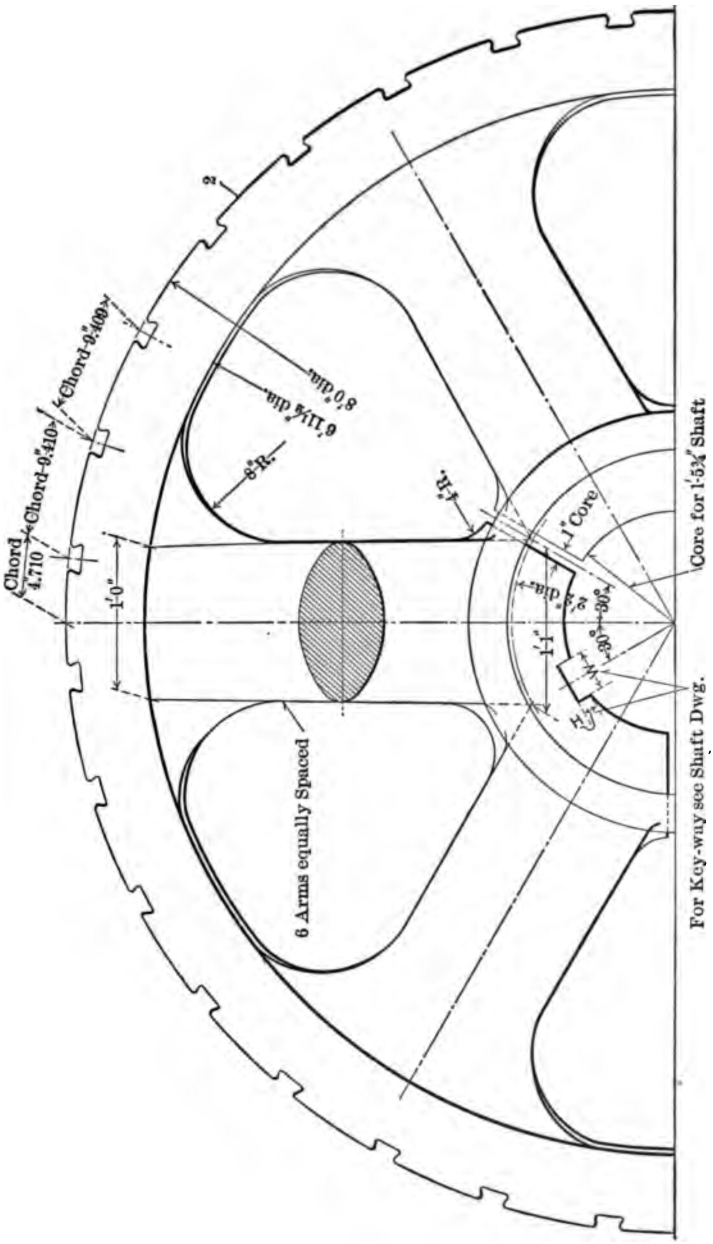


FIG. 72.—Pole-wheel of a Large Generator (Westinghouse).

Calculate the regulation for $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, $1\frac{1}{4}$ and $1\frac{1}{2}$ loads, and for unity power factor. Also calculate the regulation for full load and for 80 per cent power factor.

(W) Efficiency

Assume the windage and bearing friction losses and calculate the efficiency at various loads. These losses are very difficult to predetermine with even a reasonable degree of accuracy. They vary widely in similar machines of the same type, speed and capacity. For high-speed belt-driven machines, ranging in speed from 900 r.p.m. to 1200 r.p.m. those losses should range from 1.5 to 3.5 per cent. For engine-type machines running at from 125 to 360 r.p.m. they should range from $\frac{1}{2}$ of 1 per cent to 1.5 per cent. For very large slow-speed machines with good alignment it might be even less.

The efficiency may be obtained by the following formula:

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}. \tag{54}$$

Tabulate the losses and efficiency as follows:

Load in Per cent.	Arm. I^2R.	Field I^2R.	Core Losses	Windage and Bearing Friction.	Total Losses.	Efficiency in Per cent.
0						
25						
50						
75						
100						
125						
150						

The temperature rise of the armature and of the field at various loads should be calculated by the methods already given and curves plotted showing the results.

The remaining mechanical details are to be worked out on the drawing board as the work proceeds.

CHAPTER III

DESIGN OF ROTARY CONVERTERS

The design of a rotary converter is carried out along the same lines as that of a direct-current generator, except that not nearly so much armature copper is required because of the fact that the current the machine requires as a synchronous motor offsets to a greater or less degree, depending upon the number of phases and the power factor, the current which the machine delivers as a direct-current generator. Also, collector rings must be added to conduct the alternating current to the proper points in the armature winding, and the number of poles is usually fixed by the frequency.

The design of direct-current generators was covered in Volume I, and synchronous motors in Chapter II of this volume, therefore it will be necessary to discuss only a few points in connection with rotaries.

Since the speed is not fixed by any type of prime mover, the speed is usually higher and the poles fewer with more slots per pole per phase. For example, a certain 300-kilowatt, 3-phase rotary has 4 poles and runs at 750 r.p.m. and there are 8 armature slots per pole per phase.

The following relation exists between the armature copper losses in a D.C. generator and in a rotary converter. Assuming the losses in a direct-current generator equal to unity, the losses in a rotary for unity power factor are as follows:

Single-phase = 1.38
Two-phase = 1.38
Three-phase = 0.56
Four-phase = 0.38
Six-phase = 0.27

For 80 per cent power factor, the values are as follows:

Single-phase = 2.50
Two-phase = 2.50
Three-phase = 1.23
Four-phase = 0.94
Six-phase = 0.77

The alternating E.M.F. available between adjacent slip rings in rotary converters in terms of the direct voltage is as follows:

Single-phase = 0.707
Two-phase = 0.707
Three-phase = 0.61
Four-phase = 0.50
Six-phase = 0.353

The above values are based on a sinusoidal field. For a rectangular field with the poles covering about 70 per cent of the armature surface, they would be about 5 per cent higher.

A six-phase rotary may be supplied from a three-phase line through three transformers as indicated in Fig. 73 and Fig. 74.

Rotary converters of any considerable output are usually six-phase. Six-phase rotary converters have the following advantages.

(1) A higher rating, therefore they are smaller and cheaper for a given output.

(2) The magnetizing effects of the currents in the armature are more nearly balanced, therefore the commutation is better.

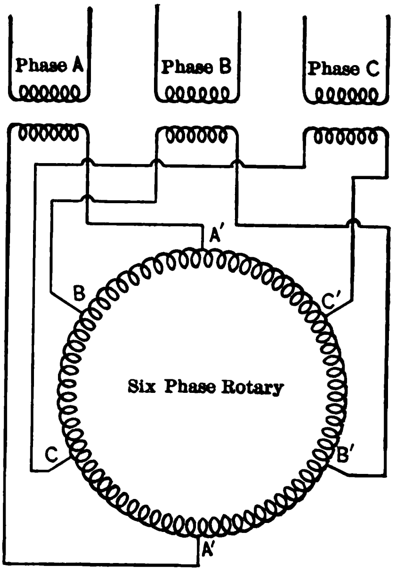


Fig. 73.

(3) They run more stably than rotaries with fewer phases. There is less tendency to "hunt."

Damper Winding.—In order to prevent hunting, it is essential that the poles of a rotary converter be equipped with a damper winding. Hunting is usually started by some outside force, as, for example, a sudden increase in the load on the rotary which makes its armature drop back relative to the synchronous relation of the field. The next instant it will swing ahead, and unless some force tends to make it retain its fixed relative position it will continue to surge back and forth. The damper winding on the field poles has this retaining force, since for any relative movement between the rotation of the armature and of the field, an E.M.F. will be induced in the bars of the damper winding which will cause a current to flow that will set up a field that will counteract the field set up by the surging. An

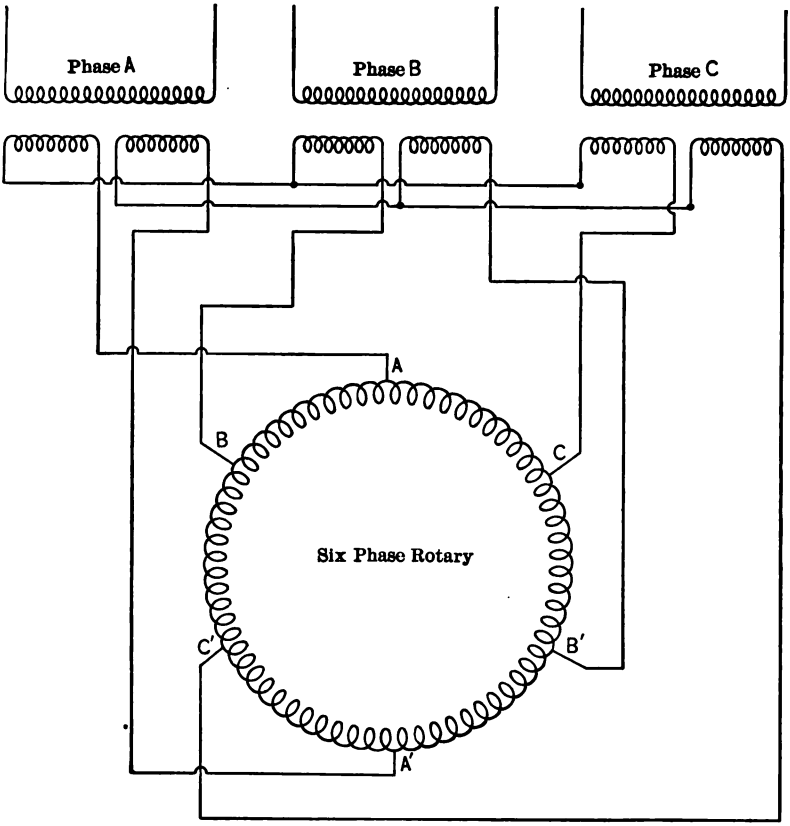


FIG. 74.

excellent damper winding is obtained by putting on a winding similar to that used on the armature of the squirrel-cage type of induction motors.

The rotary may be started from the direct-current side similar to a direct-current motor and synchronized on the alternating-current side the same as an alternating-current generator, or it may be started by means of a small induction motor, connected direct to the shaft of the rotary. After being brought up to speed it has to be paralleled both on the direct-current and alternating-current side; or it may be started as an induction motor by impressing alternating current on the armature of the converter. The

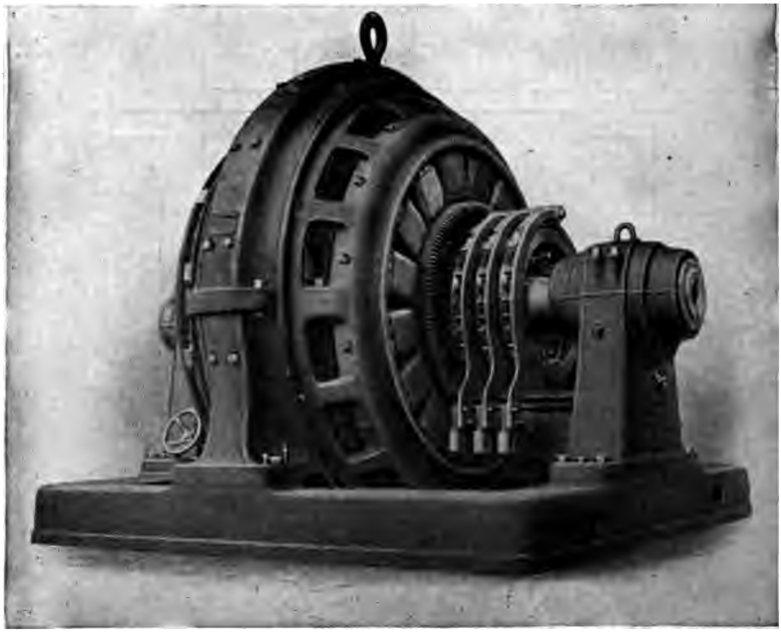


FIG. 75.—1000 K.W. Six-phase Rotary Converter (Westinghouse).

damper winding will then act as the secondary of an induction motor, and the converter will speed up. This is a most convenient way of starting and the method most commonly used.

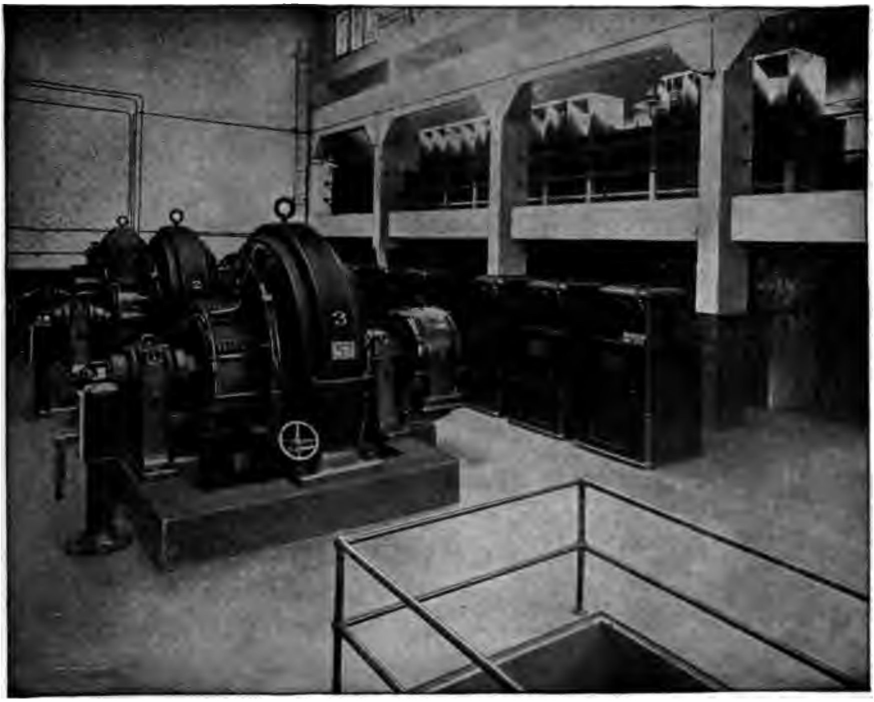


FIG. 76.—Rotaries in Sub-station, Capitol Traction Co., Washington, D. C. (Westinghouse).

Compounding of the Rotary Converter

It has been said that the ratio between the alternating-current voltage and the direct-current voltage of a rotary is fixed. A certain amount of variation may be obtained through variation of the exciting current of the rotary, in conjunction with reactance available in the armature circuit. This is to be understood as follows:

A rotary converter running off the alternating-current circuit may be regarded as a synchronous motor. There is a certain fixed field current at which the rotary will draw the smallest alternating current from the line. This corresponds to unity power factor.

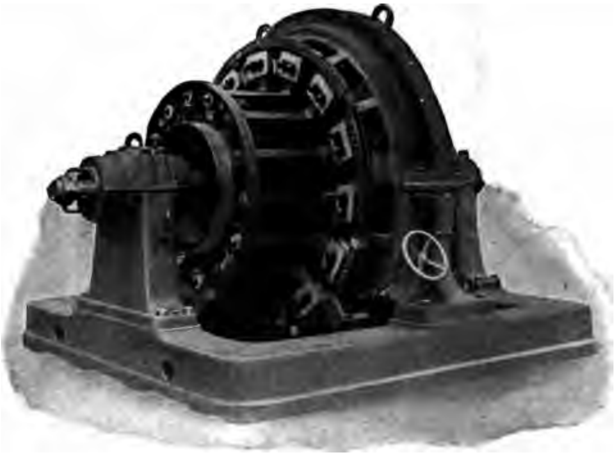


FIG. 77.—Self-starting Rotary Converter 750 K.W. Six-phase, 60-cycle (Westinghouse).

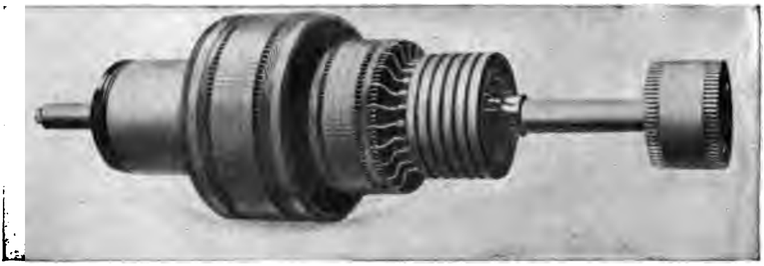


FIG. 78.—Rotor with Synchronous Regulator Armature and Starting Motor Rotor, 770 K.W. (Westinghouse).

If this field current is changed, the current from the line is changed also. By increasing the field current, the rotary is made to draw a leading current from the alternating-current circuit, and by decreasing the field current, it is made to draw a lagging current from the circuit.

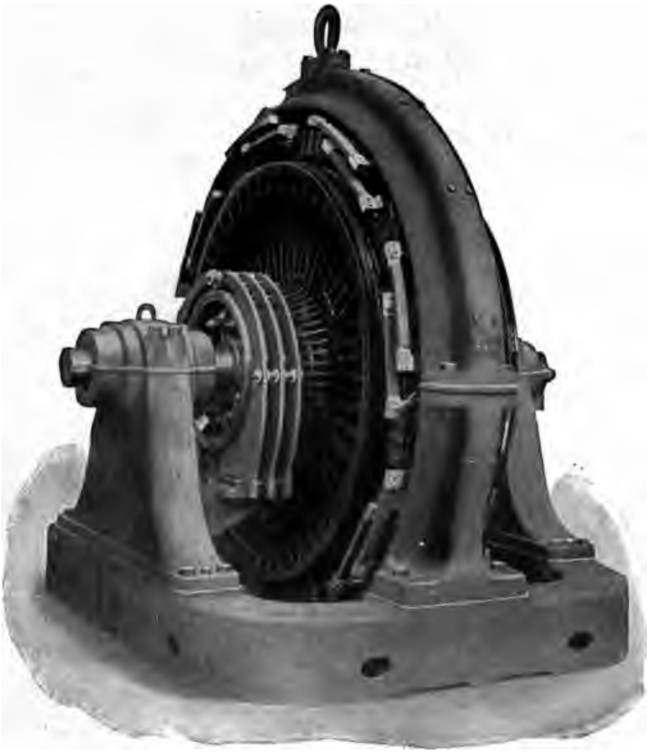


FIG. 79.—3000 K.W. Self-starting Rotary Converter, 600-volt (Westinghouse).

Assume now that the rotary is over-excited. It delivers a leading wattless current to the line. This current in conjunction with reactance in the circuit will cause an inductive drop in the rotary armature which has an influence upon the impressed alternating-current voltage of the converter. This effect is to raise the impressed rotary voltage. Similiarly underexcitation will cause a lowering of the impressed voltage. Thus a certain amount of variation can be obtained by introducing wattless currents in the rotary armature and by providing for a certain amount of reactance. Of course such a procedure tends to increase the heating of the converter armature and causes the converter to operate at power factors other than unity. However, it is possible to obtain a certain amount of automatic regulation in this manner without injury to the rotary or without bad effects upon the circuit on which it operates.

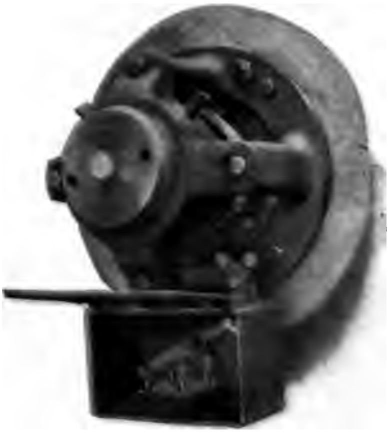


FIG. 80.—Oscillator and Speed Limit Device, Switch Open (Westinghouse).

It is not unusual to provide a series field winding on the poles which automatically increase the excitation, as the load comes on and tends to hold up the voltage on the direct-current side, even if the alternating-current voltage should drop off slightly on account of the line drop. Furthermore, there is often provided from 10 to 25 per cent reactance in the converter circuit.

Oscillators.—In order to prevent the brushes wearing channels in the commutator and collector rings, some form of oscillating device should be provided to produce a periodic axial movement of the armature and shaft. In Fig. 80 is shown a Westinghouse oscillator.

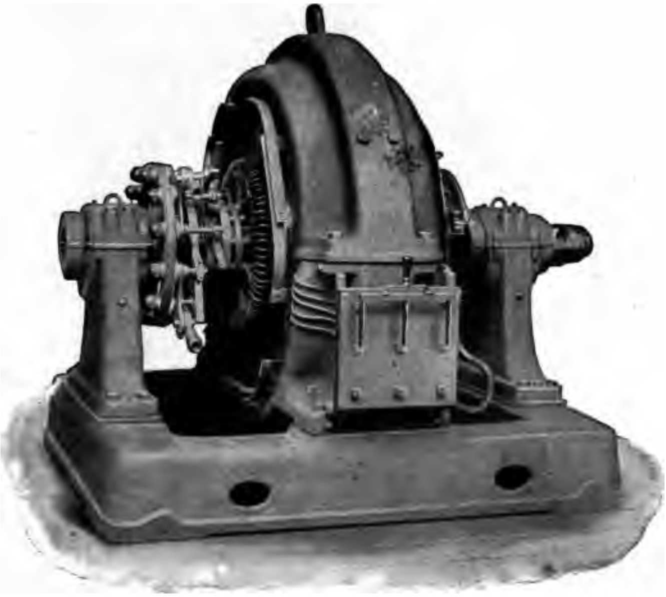


Fig. 81.—Self-Starting Rotary, 200 K.W., 600-volt, 60-cycle (Westinghouse).

It consists of a steel plate with grooved ball race and ball backed by a spring. As the grooved plate is not quite parallel to the end of the shaft, when the rotary is properly installed with the armature slightly inclined toward the oscillator, the hardened steel ball is caught at the lowest point between the race and the end of the shaft. As the

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armature revolves, the ball is carried upward, and the spring compressed. The reaction of the spring forces the shaft away and the ball falls back to its normal position. Thus, a periodic longitudinal motion, of a frequency determined by the natural period of the motor, is imparted to the armature as it revolves and uniform wear of commutator and collector rings is assured.

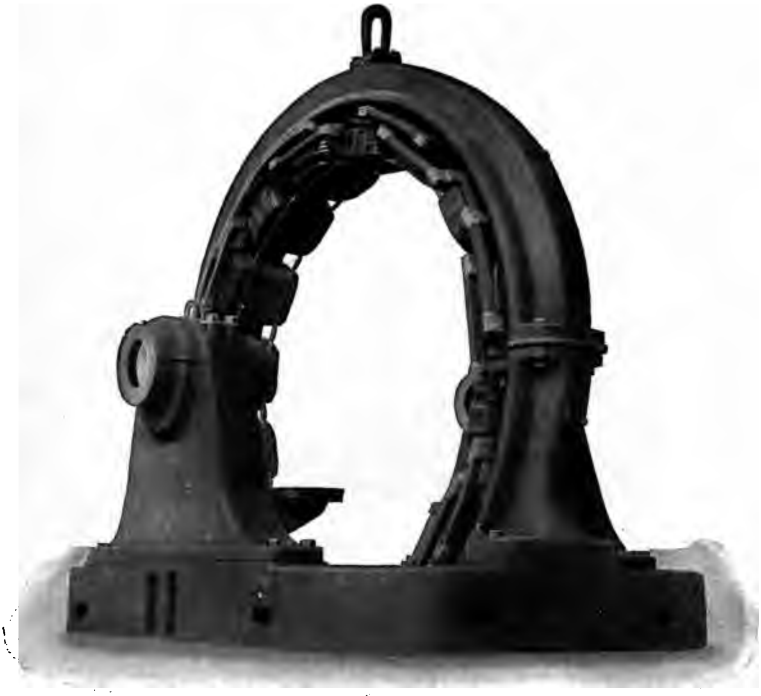


FIG. 82.—Stator of 3000 K.W., Six-phase Rotary Converter (Westinghouse).

Overspeeds.—As a safeguard against overspeeds in rotary converters, a safety device consisting of a spring-closed knife switch actuated by a centrifugal tripping mechanism is attached to the same end of the shaft as the oscillator. The knife switch is held open by a pivoted latch so arranged that when the simple centrifugal governor attached to the shaft operates at a predetermined speed, it trips the latch and releases the spring, thus insuring a quick and positive closing of the switch. This switch is contained in a metal box attached to the bearing housing and completes an auxiliary circuit through the tripping coils of the direct-current circuit-breakers.

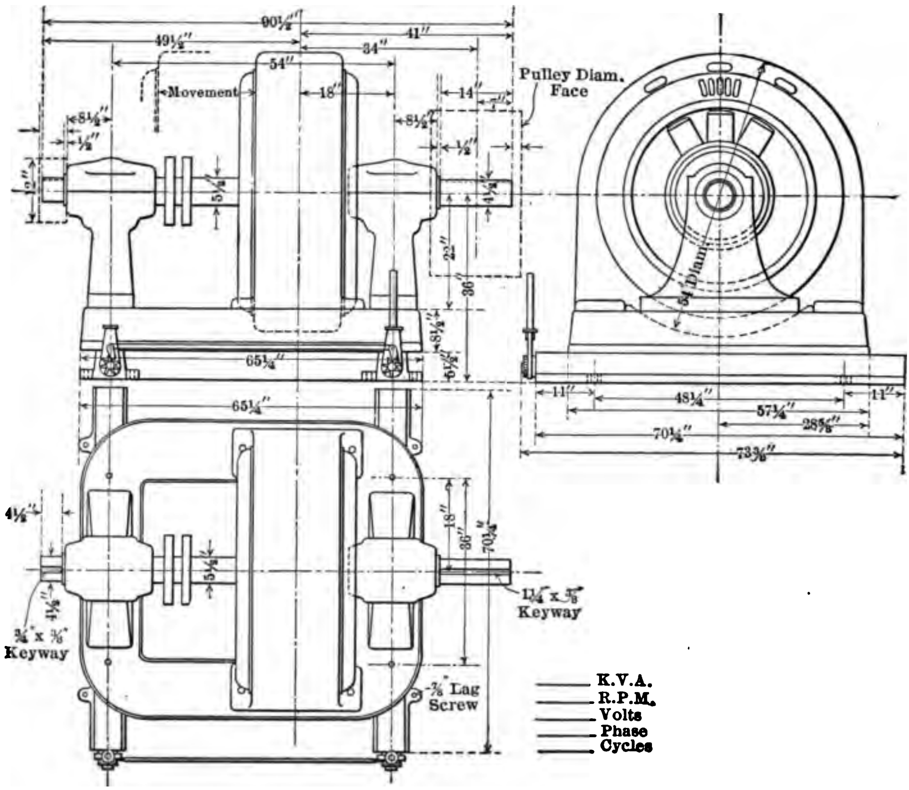
Field Break Switch.—If a rotary is started from the alternating current side, it should be provided with a double-throw field switch so that during starting the field may be opened in several places, so as to reduce the strain on the insulation that might otherwise result from the high voltage induced in the field coils. When the alternating-current switches are closed on a self-starting rotary, the rotary is virtually a transformer, the armature winding acting as the primary, and the field winding as the secondary. This transformer action becomes less and less as the speed increases and entirely disappears at synchronism, but at the instant of the potential induced in the field coils may easily reach a dangerous value unless the field circuit is opened.

CHAPTER IV

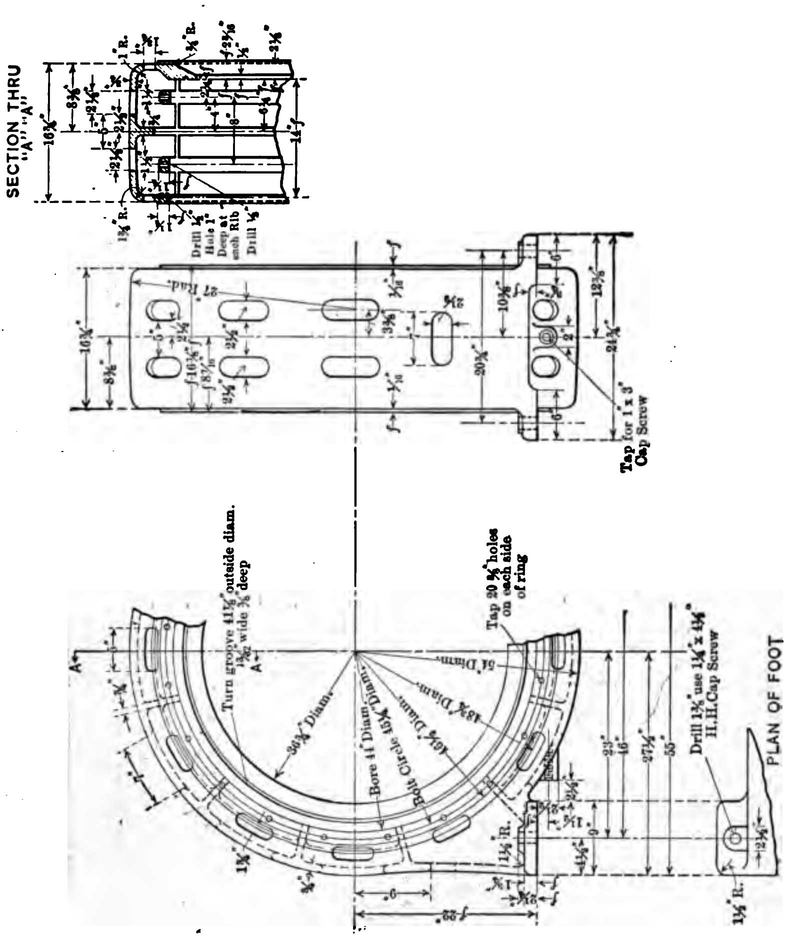
A 180 K.V.A., 600 R.P.M., THREE-PHASE, 2200-VOLT, 60-CYCLE, TWO-BEARING PEDESTAL TYPE ALTERNATING CURRENT GENERATOR.

The author is indebted to Mr. Truman Hibbard of the Electric Machinery Co., Minneapolis, Minn., for the set of actual working drawings shown in this chapter.

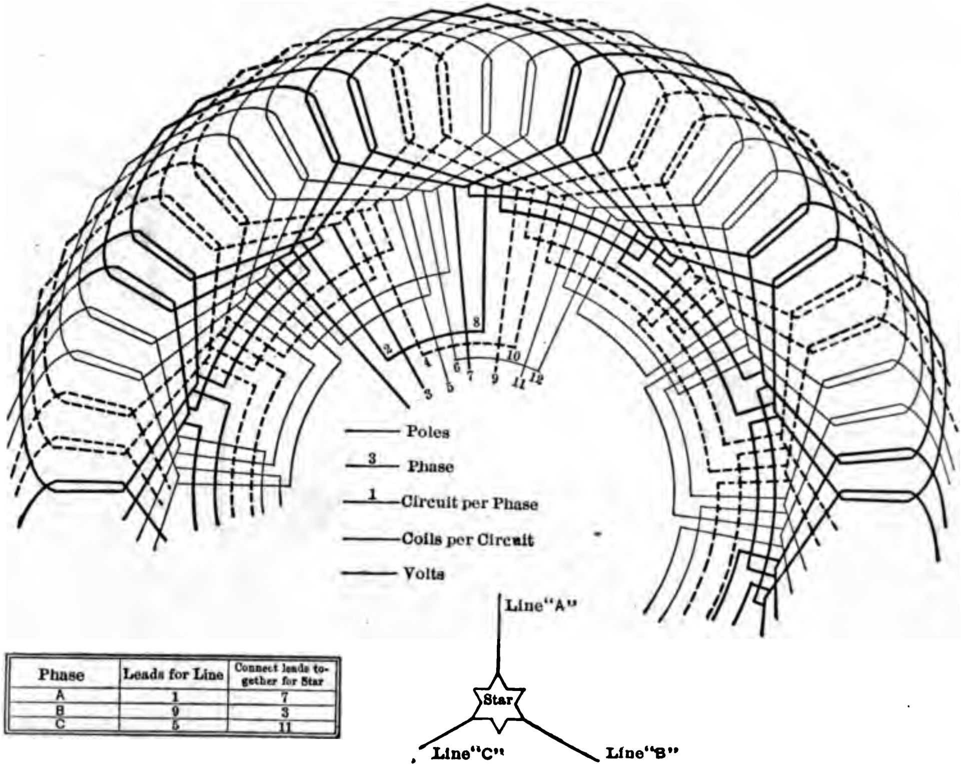
LOCATION SKETCH



ARMATURE RING—CAST IRON.

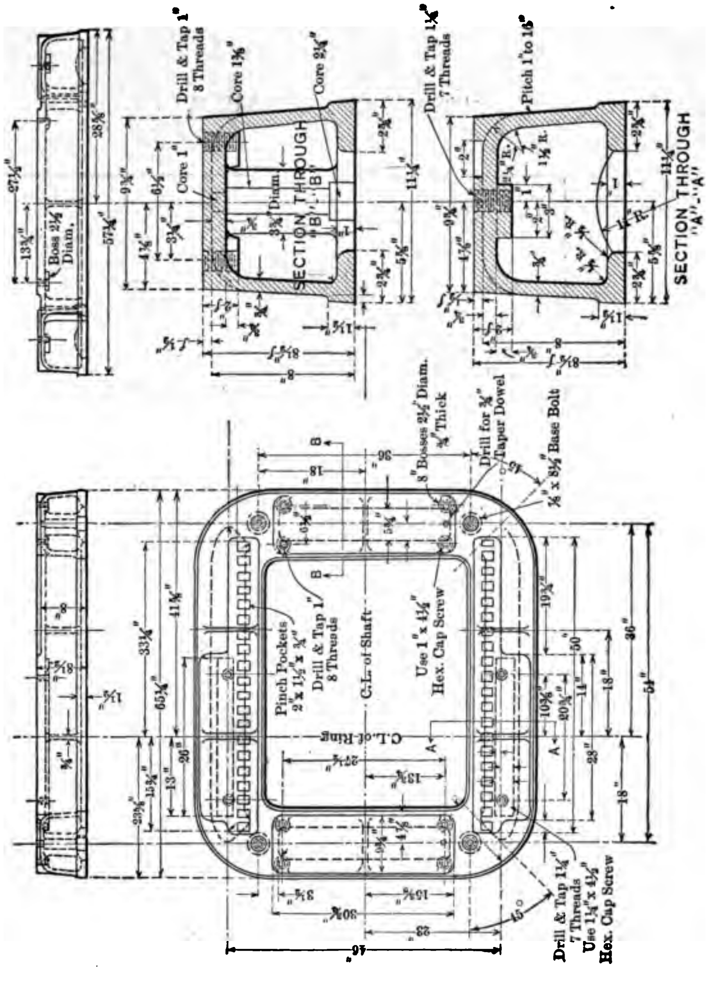


CONNECTION DIAGRAM.

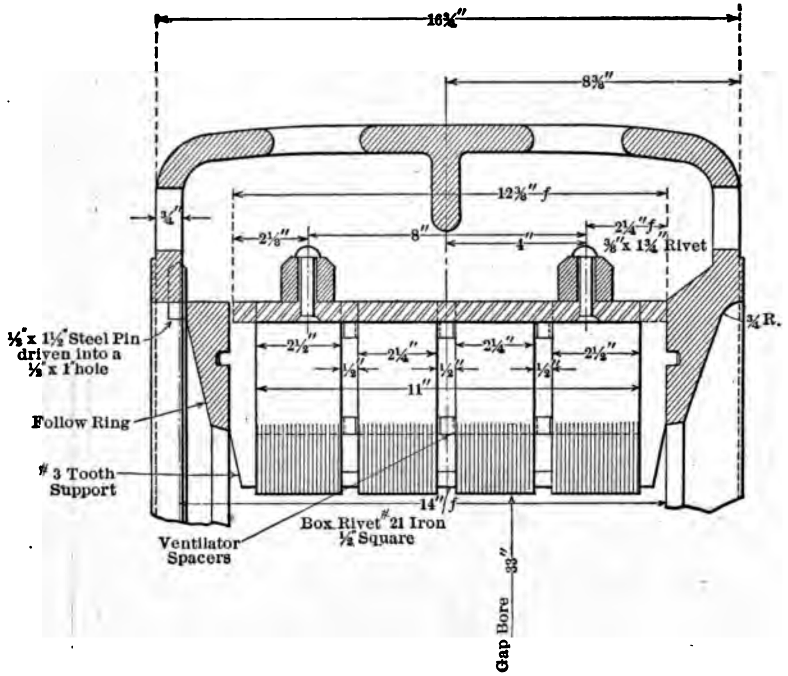


Phase	Leads for Line	Connect leads together for Star
A	1	7
B	9	3
C	5	11

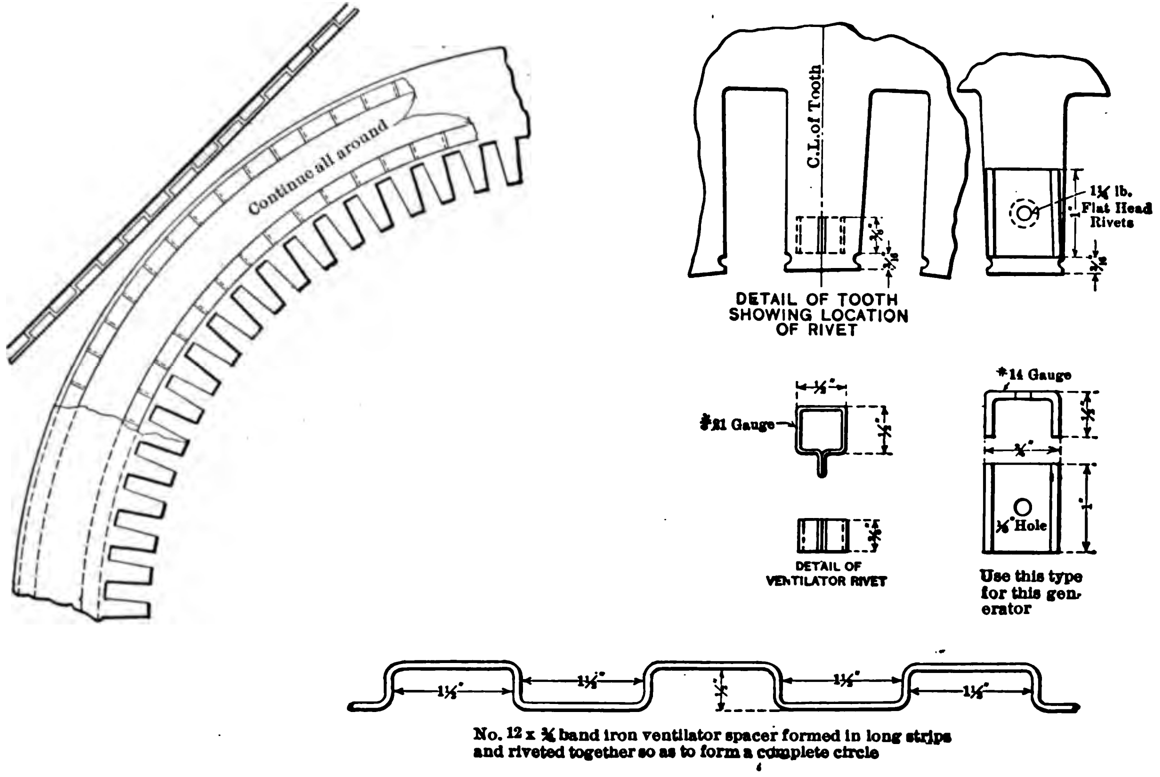
DETAIL OF BASE—CAST IRON.



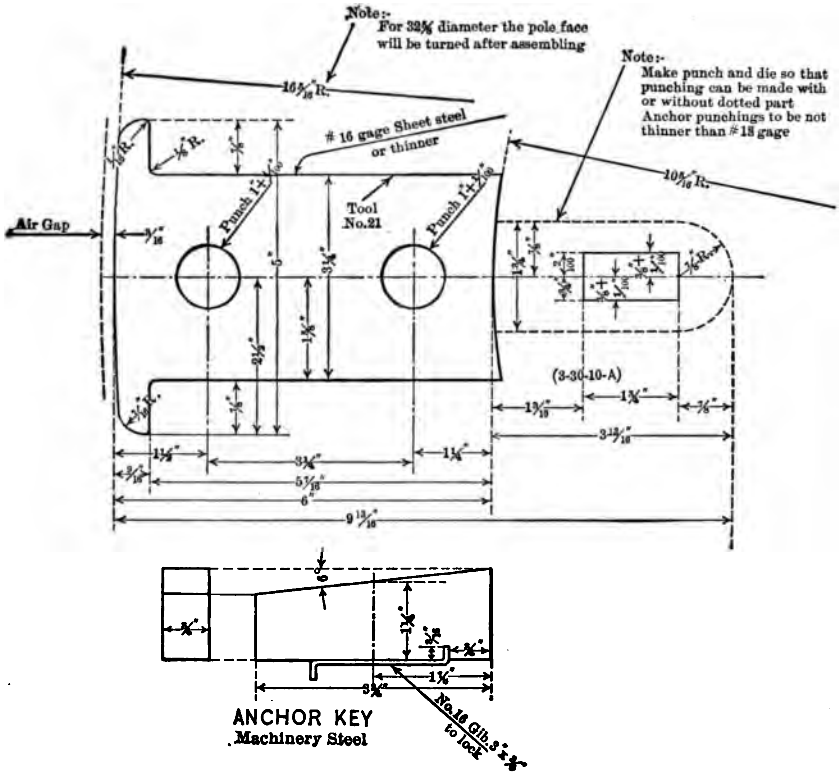
ASSEMBLED ARMATURE.



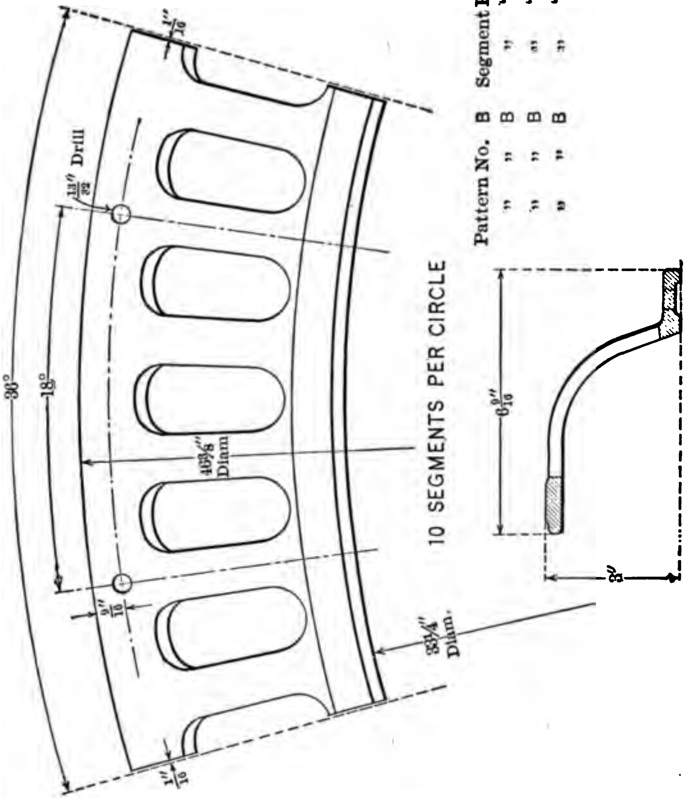
DETAIL OF VENTILATOR.


Continue all around
C.L. of Tooth
⅝"
³⁄₁₆"
DETAIL OF TOOTH SHOWING LOCATION OF RIVET
1¼ lb. Flat Head Rivets
1"
³⁄₁₆"
½"
#21 Gauge
½"
⅝"
DETAIL OF VENTILATOR RIVET
#14 Gauge
½"
¾"
1"
⅛" Hole
Use this type for this generator
1½"
1½"
½"
1½"
1½"
No. 12 x ¾ band iron ventilator spacer formed in long strips and riveted together so as to form a complete circle

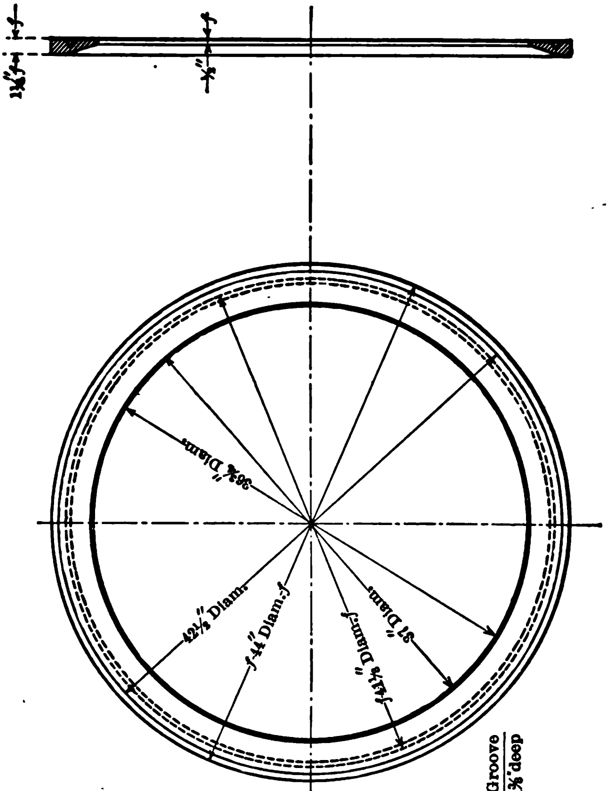
POLE PIECE PUNCHING.



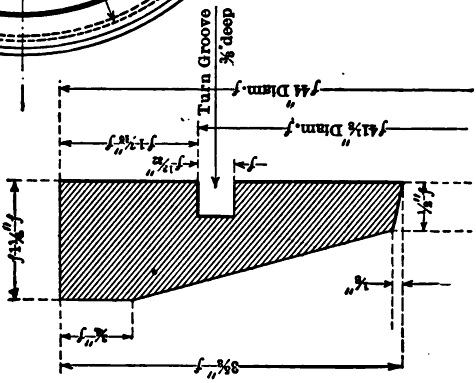
GUARD RING SEGMENT.



Pattern No.	B	Segment	Plain
" "	B	"	"Electric"
" "	B	"	"Machinery"
" "	B	"	"Company"

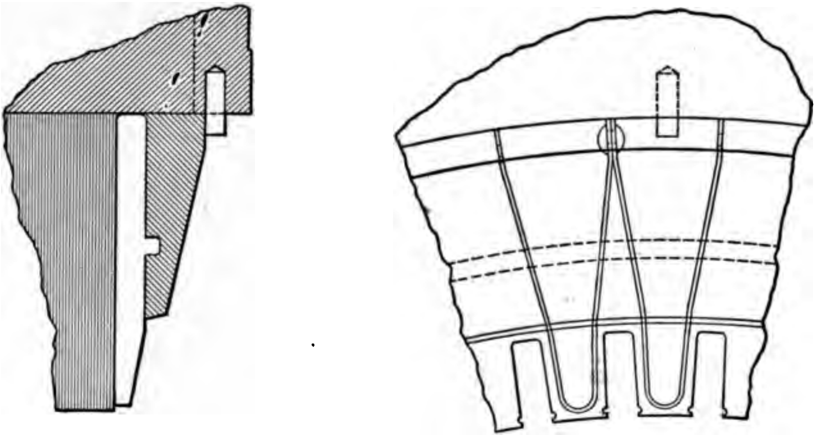


FOLLOW RING.

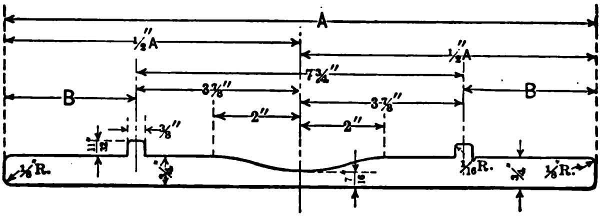


SECTION OF RING

ARMATURE TOOTH SUPPORT.

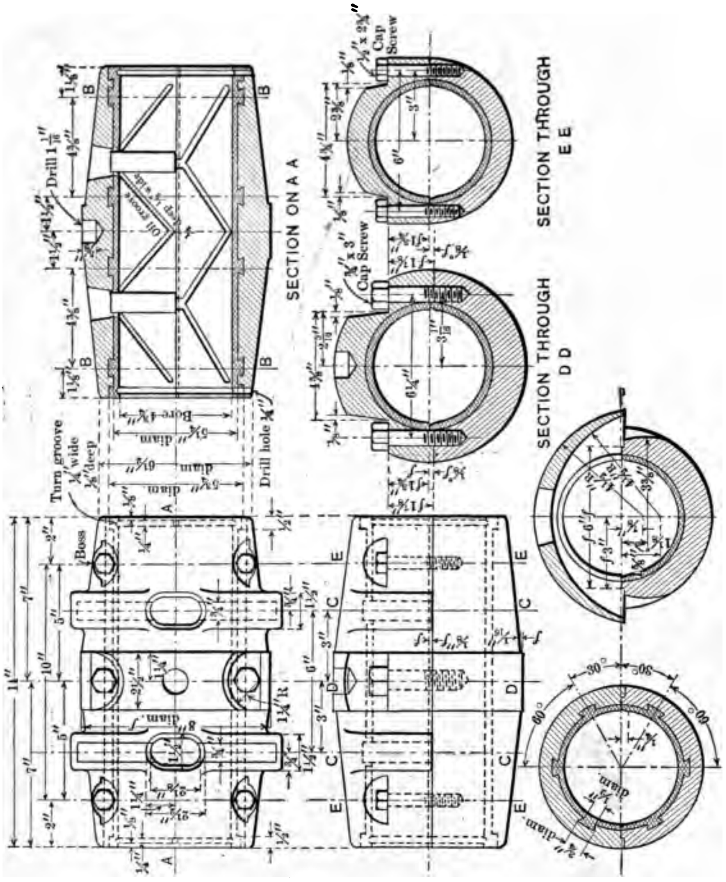


PARTIAL SECTION OF ARMATURE
SHOWING FINGERS IN PLACE

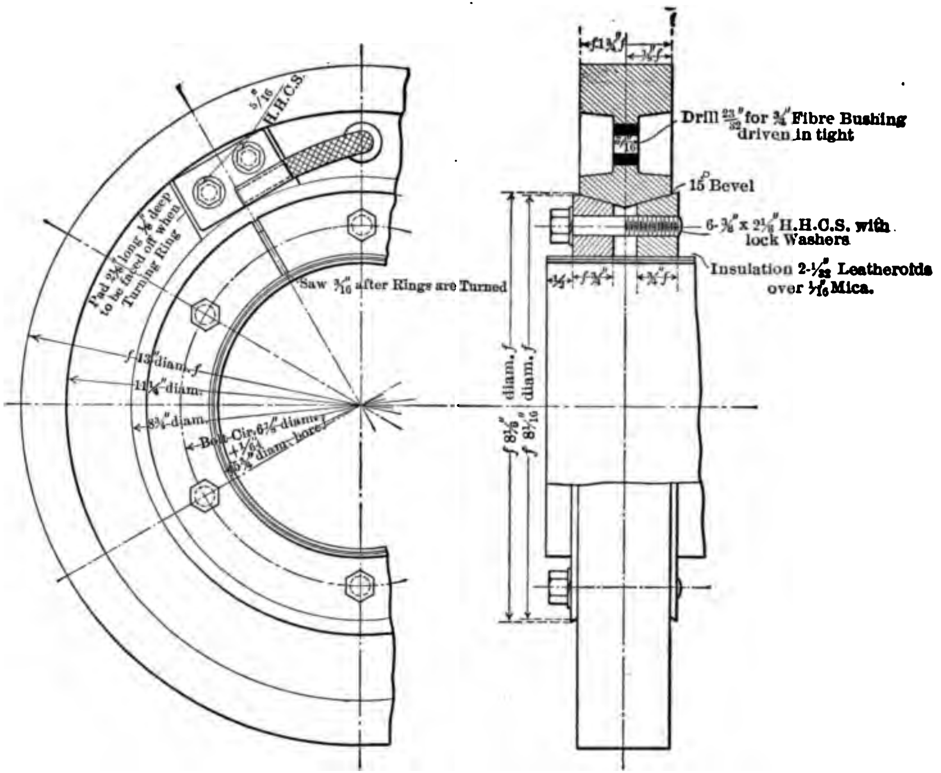


DETAIL OF FINGER PUNCHING
No. 14 Sheet Steel
A = Width of Lamination x 2" = 11"
B = 1⅝"
Crimp punching before folding
Maximum Length A = 14"

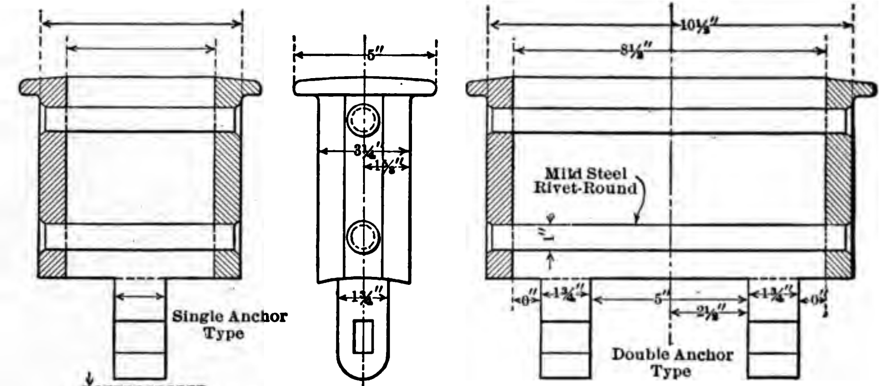
BEARING SLEEVE DETAIL.



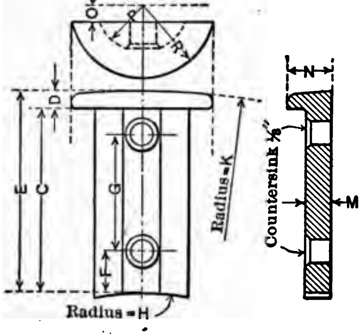
COLLECTOR RING.


5/16" H.H.C.S.
Pad 2⅜" long ⅛" deep to be faced off when Turning Ring
Saw 3/16" after Rings are Turned
13" diam.
11⅜" diam.
8¾" diam.
Bolt Cir. 6⅞" diam.
5⅝" diam. bore + 1/64"
8½" diam.
8 1/16" diam.
1⅜"
⅞"
Drill 23/32" for ¾" Fibre Bushing driven in tight
7/16"
15° Bevel
6-⅜" x 2⅛" H.H.C.S. with lock Washers
Insulation 2-1/32" Leatheroids over 1/16" Mica.
½"
⅜"
⅜"

ASSEMBLED POLE AND END PLATE.



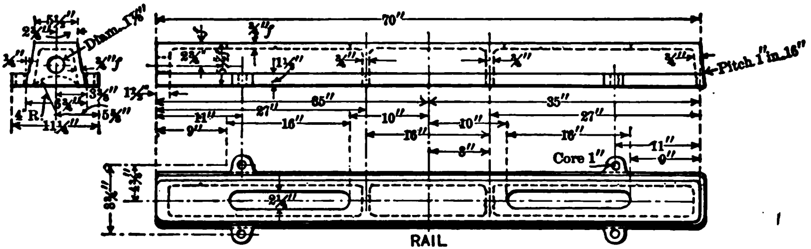
Pole wound with – X - Copper wire strip
— Turns per pole



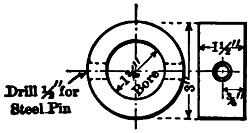
Dimensions of Pole end Plates–Cast Steel

Pat. No.	C	D	E	F	G	H	K	M	N	O	P	R	Diam. of Holes
B-873	5 5/16″	9/16″	6″	1¼″	3¼″	10 5/16″	46″	⅜″	1⅝″	⅝″	1⅝″	2½″	1 1/32″
B-793	5 5/16″	9/16″	6″	1¼″	3¼″	10 5/16″	46″	1″	2″	½″	1⅝″	2½″	1 1/32″
B-797	5⅜″	⅝″	6″	1¼″	3¼″	9½″	53″	1¼″	2 5/16″	½″	1⅛″	2 13/16″	1 1/32″

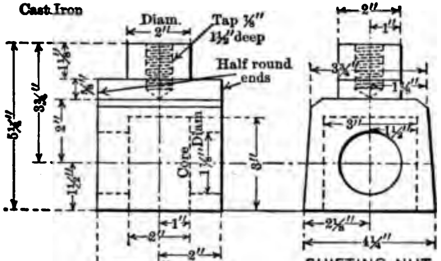
RAIL DETAILS—CAST IRON.



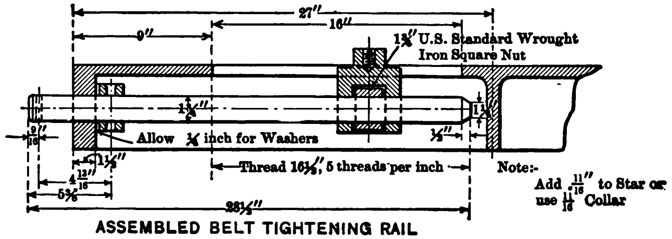
RAIL
Cast Iron



THRUST COLLAR
Cast Iron

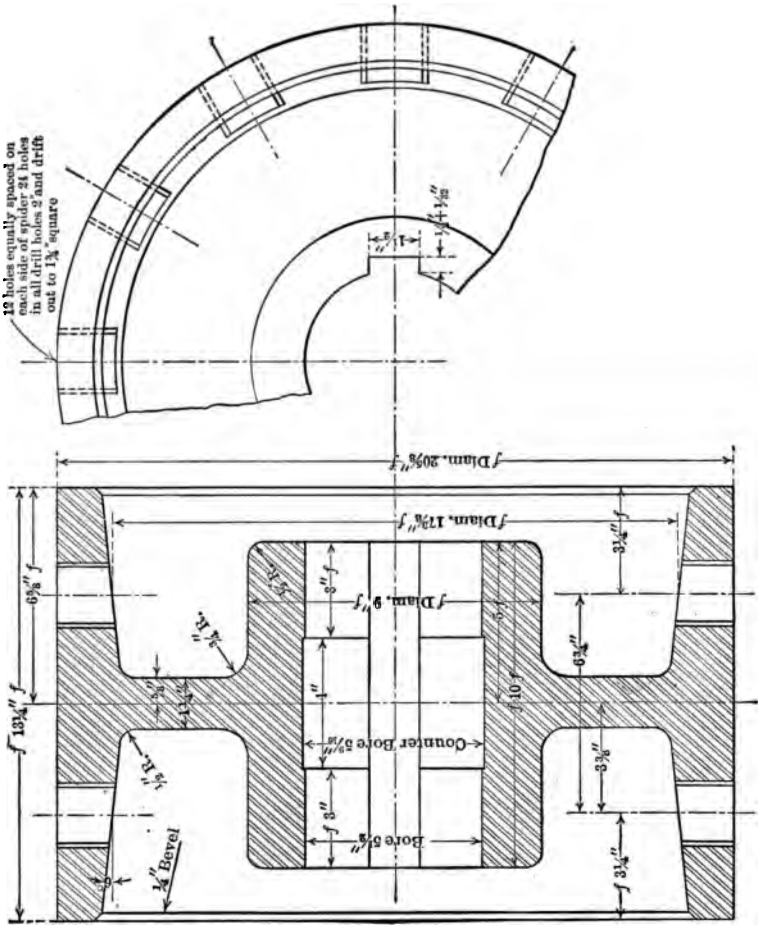


SHIFTING NUT
Cast Iron


27″
16″
9″
1⅛″ U.S. Standard Wrought Iron Square Nut
1⅛″
Allow ¼ inch for Washers
½″
1⅛″
Thread 16½″, 5 threads per inch
4 12/16
5⅝
28½″
9/16″

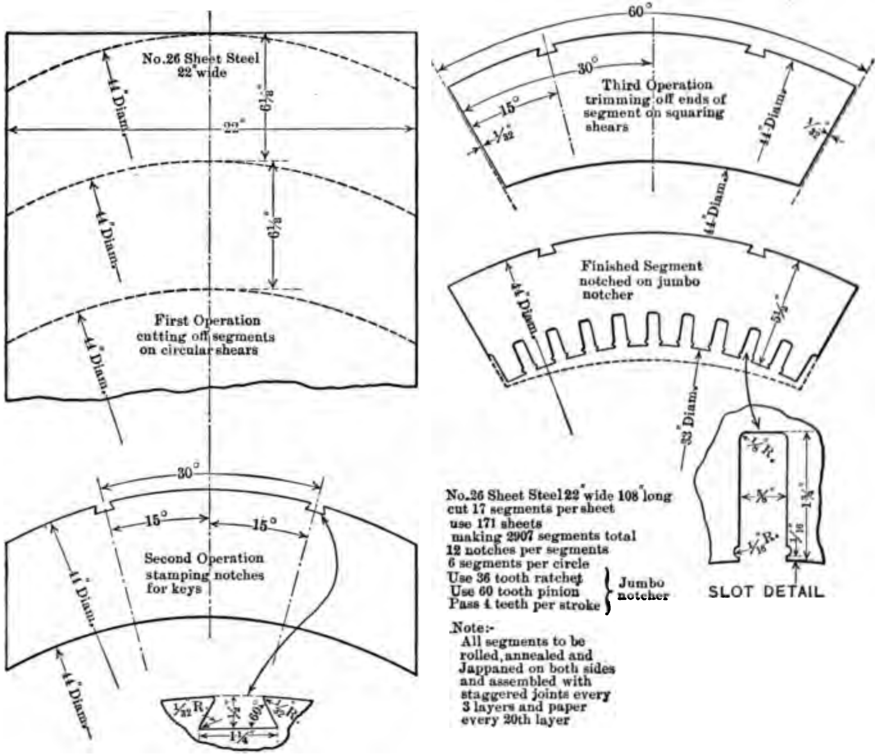
Note:-
Add 11/16″ to Star or use 11/16 Collar

ASSEMBLED BELT TIGHTENING RAIL
Cast Iron



FIELD SPIDER—CAST STEEL.

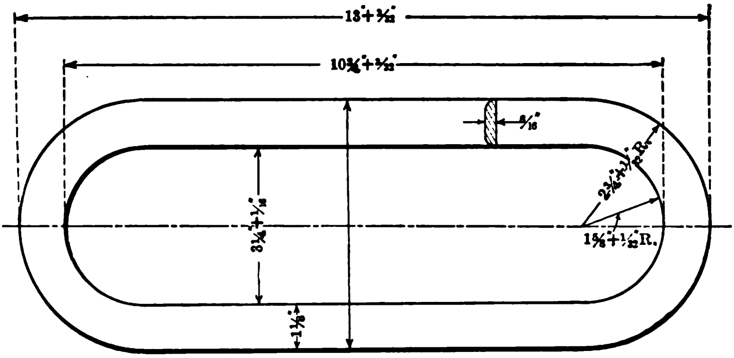
ARMATURE SEGMENT DETAIL.

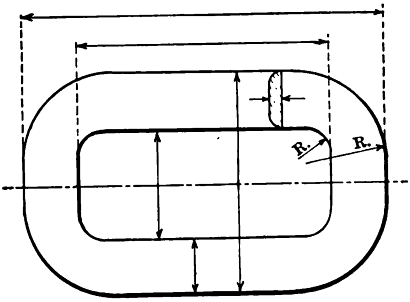


No.26 Sheet Steel 22" wide 108" long
cut 17 segments per sheet
use 171 sheets
making 2907 segments total
12 notches per segments
6 segments per circle
Use 36 tooth ratchet } Jumbo
Use 60 tooth pinion } notcher
Pass 4 teeth per stroke }

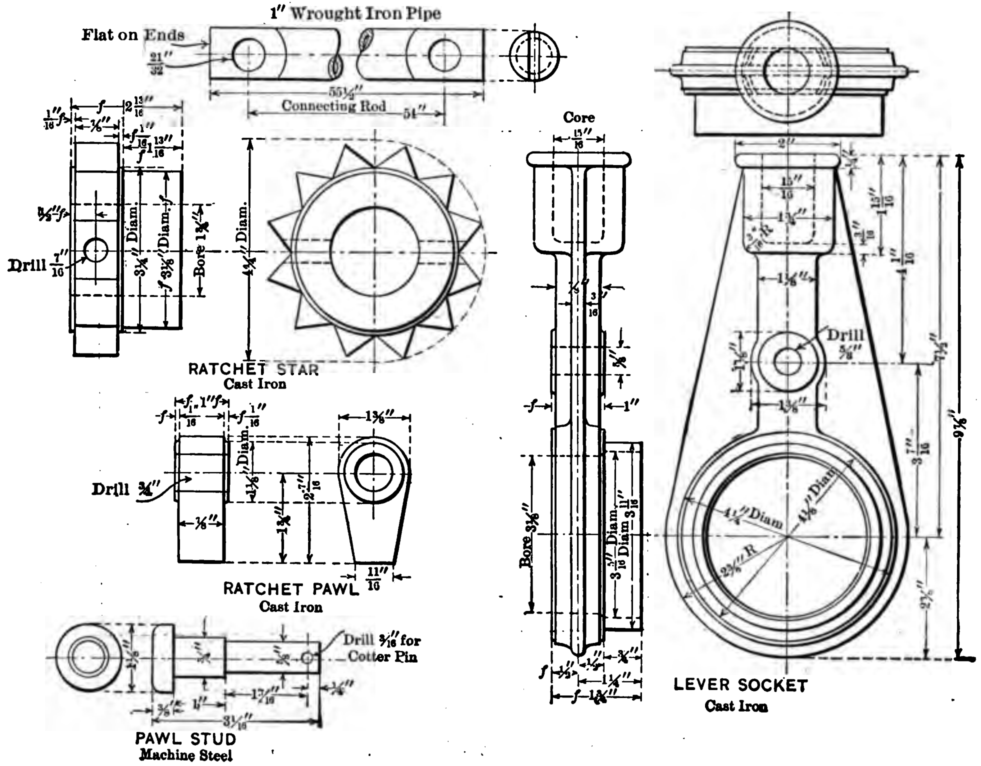
Note:-
All segments to be
rolled, annealed and
Jappaned on both sides
and assembled with
staggered joints every
3 layers and paper
every 20th layer

FIELD FLANGE—CAST BRASS.

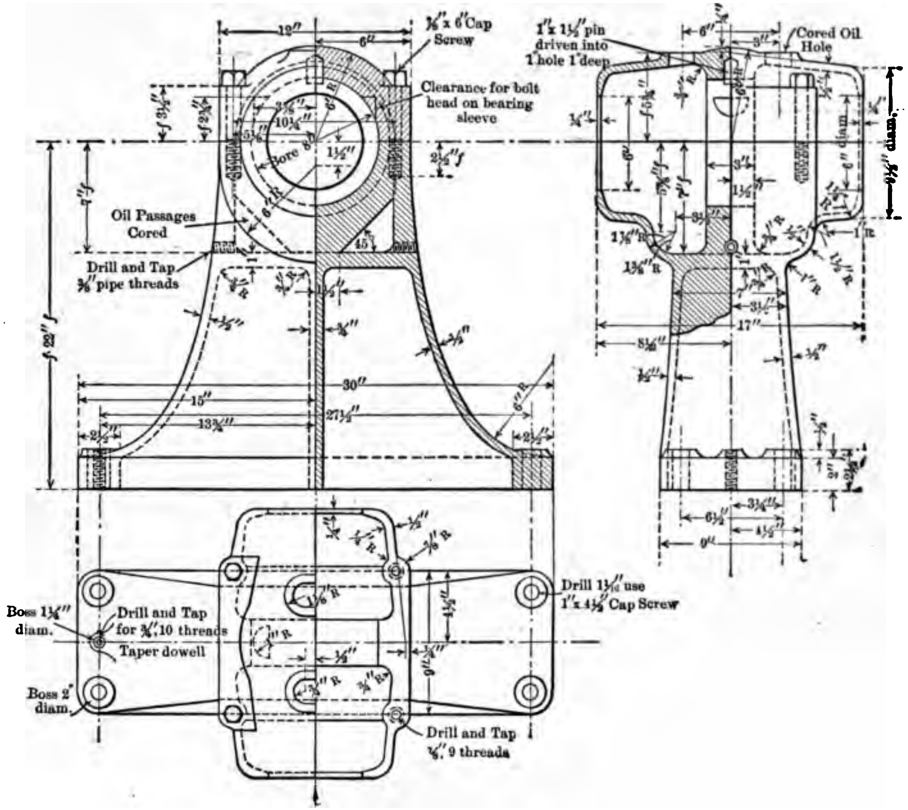




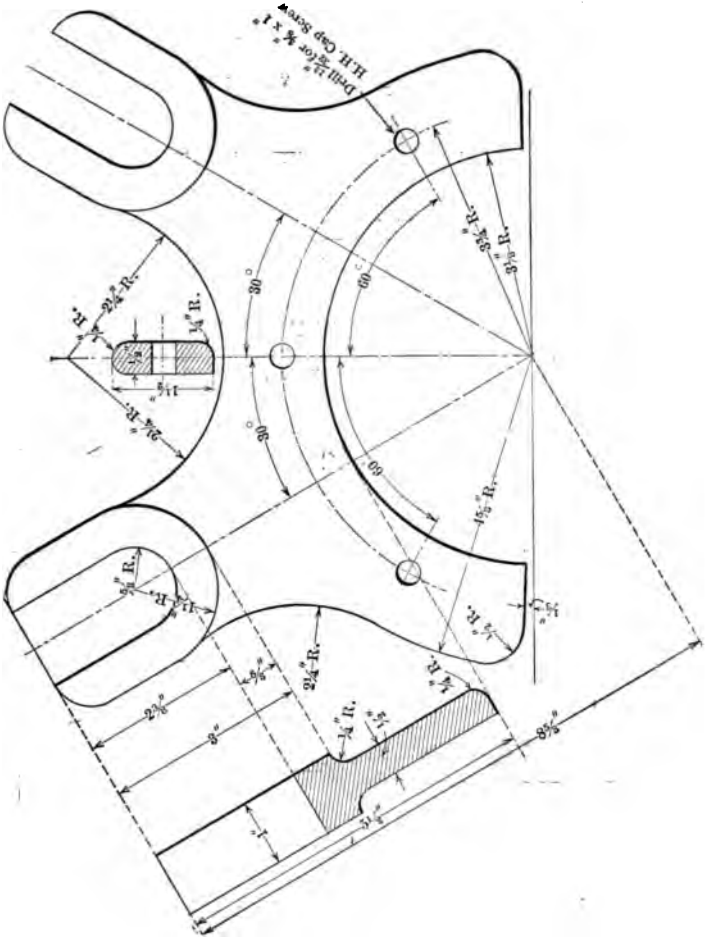
RATCHET DETAIL.



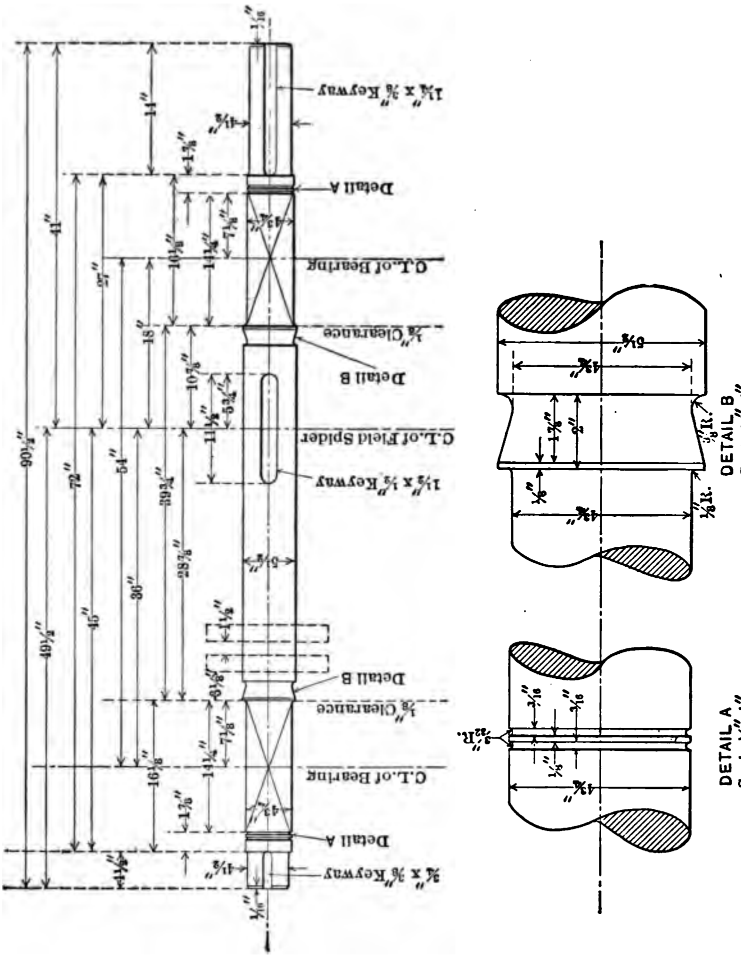
PEDESTAL AND CAP, 4¾"×14" BEARING


⅞"x 6" Cap Screw
Clearance for bolt head on bearing sleeve
Oil Passages Cored
Drill and Tap ⅜" pipe threads
Bore 8"
1"x 1½" pin driven into 1" hole 1" deep
Cored Oil Hole
Boss 1¾" diam.
Drill and Tap for ¾",10 threads Taper dowell
Boss 2" diam.
Drill 1⅛" use 1"x 4½" Cap Screw
Drill and Tap ⅞", 9 threads
12"
6"
30"
15"
27½"
13¾"
22"
17"
8½"
9"
6½"
4½"
3¼"
6" R

BRUSH YOKE—CAST IRON.



DETAIL OF SHAFT.



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